REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	1997	Final Report

4. TITLE AND SUBTITLE

Autoignition Study on Kerosene in Supersonic Flow

5. FUNDING NUMBERS

F6170896W0276

6. AUTHOR(S)

Prof. Vladimir Routovsky

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Moscow Aviation Institute
Volocolamscoe Sh., d.4
Moscow 125871 A-80
Russia

8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
PSC 802 BOX 14
FPO 09499-0200

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

SPC 96-4089

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

A

13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking Moscow Aviation Institute as follows: The contractor will investigate autoignition of kerosene as described in his proposal dated August 1996.

14. SUBJECT TERMS

Fluid Dynamics, Chemical Propulsion

15. NUMBER OF PAGES

61

16. PRICE CODE

N/A

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19, SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

AQ

MOSCOW STATE AVIATION INSTITUTE
(TECHNICAL UNIVERSITY)

Vice rector

__________ V.G. Veretennicov

«____» October 1997

CONTRACT № F61708-96-WO286

TECHNICAL REPORT
on scientific and research work

Study of kerosene autoignition

Stage III

Scientific head
Doctor of science, professor
V.B. Routovsky

Moscow, 1997

19971209 027

CONTENTS

NOTATION

M	-	Mach number;
λ	-	reduced speed;
P	-	pressure, Pa;
T	-	temperature, K;
G	-	flow rate, kg/s;
R	-	gas constant, $J/(kg \cdot K)$;
α	-	air excess coefficient at the combustion chamber, $\alpha = G_a/(G_f L_o)$;
L_o	-	stoichiometric coefficient;
τ	-	time, s.

Indices

a	–	air;
O2	–	oxygen;
H2	–	hydrogen;
CH4	–	methane;
f	–	fuel;
fh	–	fuel at the heater;
fi	–	fuel at the main combustion chamber;
h	–	heater;
s	–	autoignition;
ch	–	chemical processes;
u	–	evaporation;
I	–	autoignition delay;
*	-	parameters of the decelerated flow.

Equivalents of parameters' units

Pressure

1 at = $9.80665 \cdot 10^4$ Pa;

1 bar = 10^5 Pa;

1 kgf/cm^2 = $9.80665 \cdot 10^4$ Pa.

Gas constant

1 cal(g $\cdot$ °C) = 4.1868 J/(kg $\cdot$ K).

INTRODUCTION

The present report is drawn according to the contract number F61708-96-WO286.

The contractual work consisted of three stages.

The report on the 1st stage was devoted to the current state and the basic problems of investigation of hydrocarbon fuel autoignition processes. The review of studies on hydrocarbon fuels autoignition included 32 papers. The studied literature was used to choose the method of investigation.

The report on the 2nd stage deals with:

- scheme of the test-bench created for investigation of hydrocarbon fuel autoignition processes in the supersonic flow;
- development of method of experimental results processing;
- development of software package for experimental results processing (for *Delphi*, in *Object Pascal*).

The present report on the 3rd stage includes:

- review of the main results of the experimental investigations of ignition and burning out of the hydrocarbon fuels in the supersonic air flow (in addition to the literature review given in the report on the 1st stage);
- problem statement of experimental investigation;
- scheme of the test-bench and substantiation of choice of its basic parameters;
- analysis of the experimental investigation results.

1. REVIEW OF MAIN RESULTS OF EXPERIMENTAL INVESTIGATION OF COMBUSTION AND BURN-OUT OF HYDROCARBON FUELS-KEROSENE) IN SUPERSONIC AIR FLOW

It is known, that combustion process can be organized in two basic schemes: the scheme based on the homogeneous mixture and the scheme based on the diffusion mixture.

In the first case the organization of combustion process includes supply of liquid or gaseous fuel in an air flow, formation of a homogeneous mixture in front of flameholders, organization of stable combustion behind the flameholders, subsequent distribution of flame from the flameholders on the whole section of the chamber and burn-out of air-fuel mixture along the chamber.

For the diffusion scheme there is no phase of mixture formation, the fuel begins to evaporate and to burn as soon as it is injected into the chamber. At high temperatures (in subsonic flows and normal pressure it is ~ 1000 K) the autoignition fuel with the consequent combustion is observed. However at lower air parameters organization of stable combustion process (the stabilization) at the point of jet efflux is the important condition for effective combustion process for this scheme.

The general mechanisms of burning-out process for the above-mentioned schemes are different due to difference in the processes of flame diffusion and distribution. At the same time stabilization processes of both schemes are determined by similar physical lows, though their descriptions can have rather serious distinctions. In the supersonic flows the processes of ignition and combustion can be seriously influenced by the shock waves arising in the combustion chamber.

1.1. Diffusion combustion of hydrocarbon fuel jets

The results of the first experimental investigations showing the possibility of diffusion combustion in the supersonic flow have been published in 1960 [3]. The work studied combustion of various fuels injected into supersonic flow of wind tunnel through injector installed on the upper wall of the working body normal to the wall (fig. 1.1). The working part of the nozzle had rectangular cross-section 97.5 × 254 mm. The tests were carried out at Mach numbers 1.5; 2; 3 and 4. Air pressure at the tunnel fore-chamber varied from 2.28 at to 1.73 at, stagnation temperature was 301…316 K.

The fuel was injected in small portions (from 5 to 15 cm^2) for 1…3 seconds. Downstream of the injector there were some holes 0.7 mm in diameter, the holes allowed injecting water or hydrocarbon fuel JP-4 in to the combustion zone.

In 640 mm from the injector there was the electrical plug for the fuel ignition.

The experiments allowed obtaining stable combustion of aluminum boron hydride and JP-4 fuel containing 22 and 41 weight percents of JP-4 fuel. The mixture containing 59 % of JP-4 burned only downstream of the electrical plug. The tests with separated injection of aluminum boron hydride and JP-4 fuel has shown that the JP-4 fuel burns only in the zone of combustion of aluminum boron hydride and the combustion stops as soon as supply of aluminum boron hydride stops.

There is a lot of works devoted to experimental investigations of hydrogen combustion in the supersonic flow. They are not included into present review.

As a rule, the early works study diffusion combustion either in practically non-limited supersonic air flow or in the air flow with free boundaries. The first experiments with combustion in cylindrical channel [4] have shown that rigid boundaries influence greatly the combustion process in the supersonic flow.

That is why the study of kerosene combustion in the cylindrical scramjet combustion chamber held by ONERA, France [5] is particularly interesting.

The scheme of the experimental unit is given on the fig. 1.2. The unit had air-heater. The air was heated by burning kerosene. To recover the set oxygen proportion in the heated gas, decreasing to the kerosene burning the air in front of the heater was enriched with oxygen. Behind the heater there was a nozzle where the flow was accelerated up to $M = 2.48$. Static pressure of the flow at the inlet of combustion chamber model was 0.277 bar, static temperature $T_a = 1100$ K. The model of scramjet combustion chamber was a cylindrical tube 90 mm in diameter fastened right to the nozzle. The length of the combustion chamber could vary from 0.5 to 2 m. The air-heater and the combustion chamber model was equipped with a water cooling jacket.

Kerosene was injected to the model either through 8 holes in the wall evenly located along the cross-section right after the supersonic nozzle, or by four pylons installed on the model walls in the same cross section.

The study allowed measuring air, oxygen and kerosene flow rates, gas pressure at the outlet from the air-heater, static pressure along the model contour, static and total pressure at the outlet cross-section of the model.

If the supersonic flow at the straight channel is heated its static pressure increases and Mach number decreases. Slight increase of static pressure along the model without kerosene injection is explained by friction. With kerosene injection along the model three zones appear:

1. At the fore-part (the lower fuel excess coefficient the longer this zone is) static pressure remains the same as in the case then there is nozzle fuel. Kerosene evaporates and mixes with air but it does not burn.
2. At the middle part of the model pressure increases quickly (but constantly) due to combustion.
3. At the third zone of the model the increase of static pressure slows down, apparently it can be explained by friction.

If kerosene is injected into air flow with the above-mentioned parameters, it ignites by itself. The range of stable pressure for flow excess coefficient is rather limited.

1.2. Delay of ignition of kerosene-air mixture.

Ignition delay is an important parameter of oxidizing combustion reactions. There is a lot of works studying this parameter. The paper [6] gives a comparison of a wide range of the works, this report will single out only the most known [7,8,9].

The most interesting work on the kerosene ignition is the paper [7] studying kerosene combustion at the air flow heated by kerosene burning and without oxidizing. The ignition delay was indicated visually by distance between the injector and the spot of flame appearance.

The experiments have proved that activation energy in the poor mixture is practically independent from the air excess coefficient ($\alpha = 5 \ldots 22$), air pressure ($P = 0{,}3 \ldots 1$ bar) and drops diameter ($d = 80 \ldots 140$ μm). The evaporated kerosene was fed with the same delay, though if kerosene is heated up to 450°C, delay decreases for approximately ~ 25%. For ignition delay the following empirical dependence was received:

$$\tau = 10^{-10} P^{-1} \exp(41000 / RT) \qquad (1.1)$$

where τ – °C; P – kgf/sm^2; T – K; R = 1.987 cal/(mol · °C).

The work [8] is devoted to measurement of ignition delays in the electrically-heated air flow.

The investigation results can be generalized by the following empirical dependence:

$$\tau_i = 4.8 \cdot 10^{-16} P^0 \exp(64800 / RT) (8.5\, r_{pr} + 1)/r_{O2}, \qquad (1.2)$$

where τ – °C; P – kgf/sm^2; T – K; R = 1.987 cal/(mol · °C),

r_{p2} – volume fraction of CO_2 or H_2O in the combustion products;

r_{O2} – volume fraction of oxygen in the air.

The work [9] studies combustion in the case than heated kerosene is injected into heated air flow through an injector providing quick mixing of fuel and air. The experimental results are given as a dependence of ignition delay (results for kerosene and propane are practically the same:

$$\tau_i = 0.5 \cdot 10^{-10} P^{-1} \exp(40000 / RT), \qquad (1.3)$$

where τ – °C; P – kgf/sm^2; T – K; R = 1.987 cal/(mol · °C).

In addition to the above-mentioned studies it is necessary to single out the investigation [10] devoted to measurement of ignition delays for the reach kerosene mixture at the subsonic air flow. Heated air (T_a^* = 773…1023 K) under high pressure (5,4…11 bar) was supplied into the tube 42 mm in diameter and variable length. Swirl injector injected kerosene. The mixture compound inside the tube varied in the range of air excess coefficient α = 0,125…1.

The relative length of the combustion chamber was 16.3 of its width, therefore at average flow speed 63 m/s the fuel was in the chamber 0.01s (run-through time).

Time of ignition delay and place of ignition were determined by readings of thermocouples installed on the tube wall. It was shown that ignition temperature (at constant run-through time or at constant ignition delay time) depends on mixture compound and for the above-mentioned parameters is minimal at α = 0,3…0,7. We studied these data and came to conclusion that:

- level of delays at moderate heating (T = 1000 K) and atmospheric pressure is close to ignition delay given by B. Mullins and equals to 0.1 s;
- dependence pattern obtained after processing of these experiments if approximated for the higher temperatures does not corresponds with Mullins data, but rater close to data obtained for autoignition of liquid fuel in the diesel conditions [11].

In these condition the ignition delay time at higher temperatures is considerably longer than τ_i, derived from formulae (1,1…1,3). Probably in these

conditions the processes of two-phase heat exchange, evaporation and mixing become more important.

The work [12] study ignition of kerosene fed through an injector into supersonic air flow (M = 2.4, $T_a^* = 1200...1500$ K, $P_a^* = 3.5$ bar ($P_a = 0.23$ bar)). Liquid kerosene ignites behind normal shock wave, which appears at the supersonic flow in approximately 150 mm from the injector. The normal shock wave forms due to interaction of oblique shock waves appearing on the wedges installed on the chamber walls. The kerosene ignites in the trace behind the injector, apparently in the rich mixture. In this case behind the normal shock wave there is a luminescent zone followed by break and then by the second luminescent zone of combustion. That is why the authors call this type of combustion "two-phase" combustion. We suppose that the first luminescent zone is not the pure combustion zone, but is formed by effects or luminescence of gases during quick compression.

Thus, ignition appears at the air-fuel stream at the central part of the chamber. An average value of air excess coefficient in the chamber is α = 6,8...15. This study gives data on the air parameters behind the shock wave. The processing of these data leads to conclusion that ignition delay time in these conditions is in good correspondence with Mullins data. Therefore at fuel injection into supersonic flow the evaporation and mixing phases have nozzle serious influence on the ignition delay.

Thus the studied data lead to the following conclusions:

1. To evaluate ignition of liquid kerosene in the supersonic flow it is possible to use data of Mullins study. Therefore kerosene ignition at the supersonic flow moving, for example, at 2100 m/s ($M_a = 2.8$), $P_a = 1$ bar and $T_a = 1400$ K starts at the distance 0.2 m from the point of injection, i.e. it is quite far from the injection point.
2. If liquid fuel ignites behind the normal shock wave forming in the supersonic flow the phase of evaporation and heat exchange of liquid

drops with air apparently has a few influence on the kerosene ignition delay.

3. In the rich mixture the level of ignition delays can be considerably increased due to heat exchange between air and liquid drops and to decrease of temperature of gas phase of two-phase mixture caused by evaporation of liquid and be heating of vapors.

1.3. Ignition of liquid kerosene in the supersonic air flow

Ignition of liquid kerosene jets in the heated supersonic air flow is studied in many papers, we will consider only two of then [13, 14].

The study [13] deals with combustion of kerosene jets injected into heated supersonic air flow ($M_a = 3$, $P_a = 0.005$ bar) into cylindrical non-cooled chamber (diameter D = 110 mm, length L = 950 mm). Air was heated be kerosene heater with subsequent oxidizing. Kerosene was supplied through 6 spray injectors (d_j = 0.5 mm) in perpendicular to the air flow direction.

It is shown there that kerosene can be ignited in two ways:

1. Ignition at the stable supersonic mode of flow took place under the above-mentioned conditions if air temperature reached $T_a^* = 2500$ K, and the fuel flow rate corresponded to the air excess coefficient $\alpha \approx 1$. Under these conditions pressure increase in the form of pseudo-shock wave moved upstream, into the supersonic nozzle. Decrease of fuel flow rate (down to $\alpha = 3$) allowed to obtain pressure distribution normal for the supersonic combustion. In this case pressure increases beginning from the point of injection. After combustion it is possible to considerably decrease air temperature (down to 1600…1800 K) and maintain a stable combustion process in the chamber.
2. It is possible to obtain kerosene ignition at considerably lower air temperature if before the fuel injection the flow disturbance is organized

in the chamber (for example, by opening gate valve of the compression chamber that increases pressure both in the compression chamber and in the and of the combustion chamber) kerosene can be ignited already at $T_a^* = 1500$ K.

Combustion ceases at decrease of temperature ($T_a^* = 1400$ K), even in case of heat crisis. Decrease of the chamber length had a negative influence on the combustion process.

The study [5] deals with investigation of kerosene combustion at the supersonic flow ($M_a = 2.48$, $P_a = 0.277$ bar). Kerosene as injected from the walls of the cylindrical chamber cooled by water. Fuel was injected in two ways:

- through 8 holes along the perimeter of the chamber wall in perpendicular to the air flow;
- through 4 diamond-shaped pylons with 16 holes, symmetrically installed into the chamber (fig. 1.3).

The presented data show that to organize kerosene combustion process in the conditioned under study it is necessary to ensure rather high air temperature ($T_a^* = 2100$ K). At low flow rate ignition of kerosene starts in the rare part of the chamber, that is especially evident for the pylon fuel injection. Only at $\alpha < 2.5$ combustion zone in the form of pressure disturbances moves upstream, to the point of injection. At the farther increase of flow rate the channel is choked (fully or partly).

The analysis of the flow parameters led the authors of the study to conclusion that in the considered conditions combustion efficiency coefficient is still rather low ($\eta \approx 0,4 \ldots 0,5$).

Thus, the results of these studies have proved that if there is no disturbances of supersonic flow kerosene ignition requires rather high temperatures of air flow (at $M = 2,5 \ldots 3$ and $P_a = 0,03 \ldots 0,3$ bar air temperature have to be $T_a^* = 2100 \ldots 2500$ K). Disturbances (shock waves) considerably decrease level of temperatures required for kerosene ignition.

So, the studied data lead to the conclusion that the behavior of the fuel ignition depends on the way of its injection, but in certain conditions its evolution requires the length sufficient for termination of pre-flame processes.

1.4. Methods to intensify of kerosene ignition in the supersonic air flow

As it is obvious from the previous chapter, at atmospheric pressure level, ignition of liquid kerosene jets in case of its jet injection into supersonic air flow requires rather high air temperature. Therefore it is clear that researchers seek the way to decrease this temperature level. There are various means to do it. As it was already mentioned the shock wave in the combustion chamber (in the form of pseudo-shock waves, oblique shock waves and even normal shock wave) allow to considerably decrease level of temperatures at which ignition of kerosene starts.

Combustion of hydrocarbon fuels behind an oblique shock wave has been studied [15] in the wind tunnel with Mach number 4 at the working part (fig. 1.4). Air was heated up to 1370 K by burning kerosene. The studied fuel JP-4 was injected by various injectors placed along the axis of the supersonic nozzle right at the bottleneck. The oblique shock wave in the flow of combustible mixture was created by symmetrical wedge with half-angle 24° and 27°. During injection of liquid fuel the flow was cooled, and at the supersonic part of the nozzle the condensation shock waves.

In case of JP-4 fuel at flow temperature behind the shock wave ≈ 680 K there was a luminescence on the fore-part of the wedge. The precision measurements for these studies were not carried out. The study led to conclusion about possibility to organize detonation combustion of the regular hydrocarbon fuels behind the strong shock wave.

Even in early studies (for example [13]) it was shown that ignition improves and combustion stability increases if a few of hydrogen is injected into the chamber along with kerosene.

One of the works studying influence of hydrogen injection on the kerosene ignition was the work [16].

This work dealt with ignition of kerosene and methane in the conditions of the flat supersonic combustion chamber. Air flow parameters: $M_a = 1.98$, $P_a^* = 2.23$ bar, $T_a^* = 1800$ K. As the tests have shown in the studied conditions injection of kerosene and methane from the wall into the flow did not lead to their combustion. There was no ignition as well if kerosene was injected in front of a step approximately 12 mm high. Injection of a certain quantity of hydrogen before the main jet allowed obtaining ignition of kerosene and hydrogen at the certain proportion of hydrogen and kerosene flow rates and at certain pressure of kerosene injection. Assuming that quantity of hydrogen necessary for ignition is in inverse proportion to the scale of disturbances introduced by the main kerosene jet, the authors basing on the simplest model managed to represent the experimental results (ignition bound) as the following dependencies:

$G_{H2} / G_K = 0.047 / (P_j / P_a)^{0.903}$ for kerosene with hydrogen,

$G_{H2} / G_{CH4} = 0.113 / (P_j / P_a)^{1.515}$ for methane with hydrogen,

where G_{H2} / G_K – ratio of hydrogen and kerosene flow rates;

G_{H2} / G_{CH4} – ratio of hydrogen and methane flow rates;

P_j / P_a – ratio pressure in the kerosene or methane jets and in the supersonic flow.

Thus, at P_j / P_a less than 4…20, ratio of flow rate of hydrogen necessary for ignition to kerosene flow rate is less than 1%. Therefor injection of small portion of hydrogen close to the point of kerosene injection is quite effective way to improve kerosene ignition.

The study [17] tries to use hydrogen injection for organization of kerosene combustion in the model scramjet. The model flat scramjet was installed on the nozzle edge with M = 6 in the air flow ($T_a^* = 1500$ K and $P_a^* = 53...55$ bar). Scheme of scramjet and collector for kerosene injection are shown at the fig. 1.5. The kerosene collector was places right behind the engine diffuser and

supplementary hydrogen was injected in front of niches on the chamber walls and in front of widening section of the chamber.

The analysis of the experimental results showed that for kerosene ignition and its subsequent combustion the model requires injection of a certain quantity of hydrogen. In this case hydrogen injected, for example, in front of the niche in the studied conditions ignited by itself even at relatively low flow rates (air excess coefficient for hydrogen $\alpha \approx 10$) and led to kerosene combustion with flow rate providing nearly critical increase of pressure in the combustion chamber (air excess coefficient for kerosene $\alpha \approx 1,6...3,3$). It is necessary to stress that kerosene combustion was preceded by considerable increase of pressure in front of the niches. After kerosene injection pressure distribution in the chamber became such of pseudo-shock wave, thus the combustion took place in the turbulent flow. Then combustion process became stable hydrogen injection can be ceased. The same phenomenon was described in early works, for example [13].

Another feature noticed during combustion of kerosene and hydrogen is complicity of organization of kerosene combustion in the widening section of the chamber. It is noticed that to maintain kerosene combustion process at the widening section of the chamber it is necessary to inject into this section (or in front of it) additional hydrogen. In this case hydrogen combustion is to lead to inducing of disturbances (head part of the pseudo-shock wave) and to movement of disturbances into cylindrical section.

Thus, we presume that in this condition hydrogen combustion influenced kerosene ignition in two ways:

- as a normal pilot flame providing heated, high-temperature, reactive gas for ignition of kerosene-air mixture;
- as heat disturbance leading to appearance of shock waves (pseudo-shock wave) influencing the ignition.

As a conclusion we would like to mention a review [18], we believe that it still has a practical importance.

This review points out that one of the way to improve fuel ignition are reactive radicals emerging in the pilot flame. As a pilot burner which in the same time plays a role of fuel injector the review proposes a unit presented at the fig. 1.6. The burner has such a construction that all the fuel fed into the burner is divided into pilot fuel which burns out inside the burner and main fuel which is injected into the supersonic flow between combustion products of the burner and the air flow. Inside the burner to simplify the ignition of the pilot flame a catalyst is installed. The presented scheme shows the case then supersonic air flow is obtained by profiled external contour of the burner. But it is easy to draw out a scheme of similar burner installed in the supersonic flow. In this case the burner works as a usual ramjet with subsonic flow speed inside the burner and its combustion products ignite the main fuel. This scheme reminds the scheme of two-mode ramjet proposed in [19].

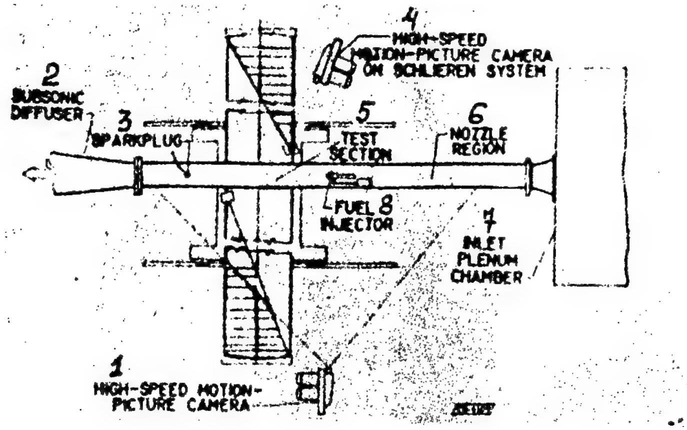


Fig. 1.1. Scheme of supersonic wind tunnel.
1 – high-speed video camera; 2– subsonic diffuser; 3 – glow plug; 4 – high-speed video camera installed in the Tepler device; 5 – working section; 6 – nozzle; 7 – fore-chamber.

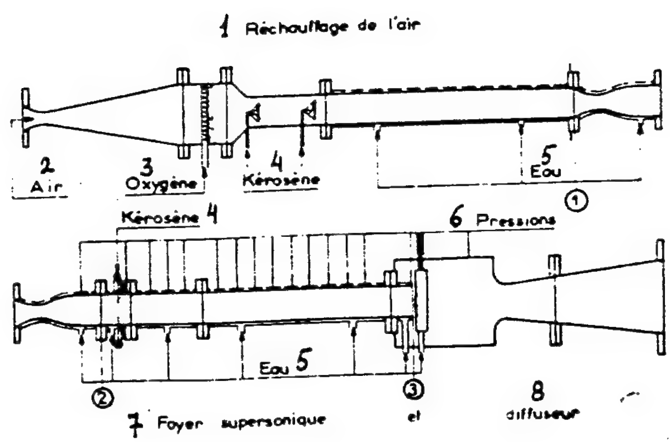
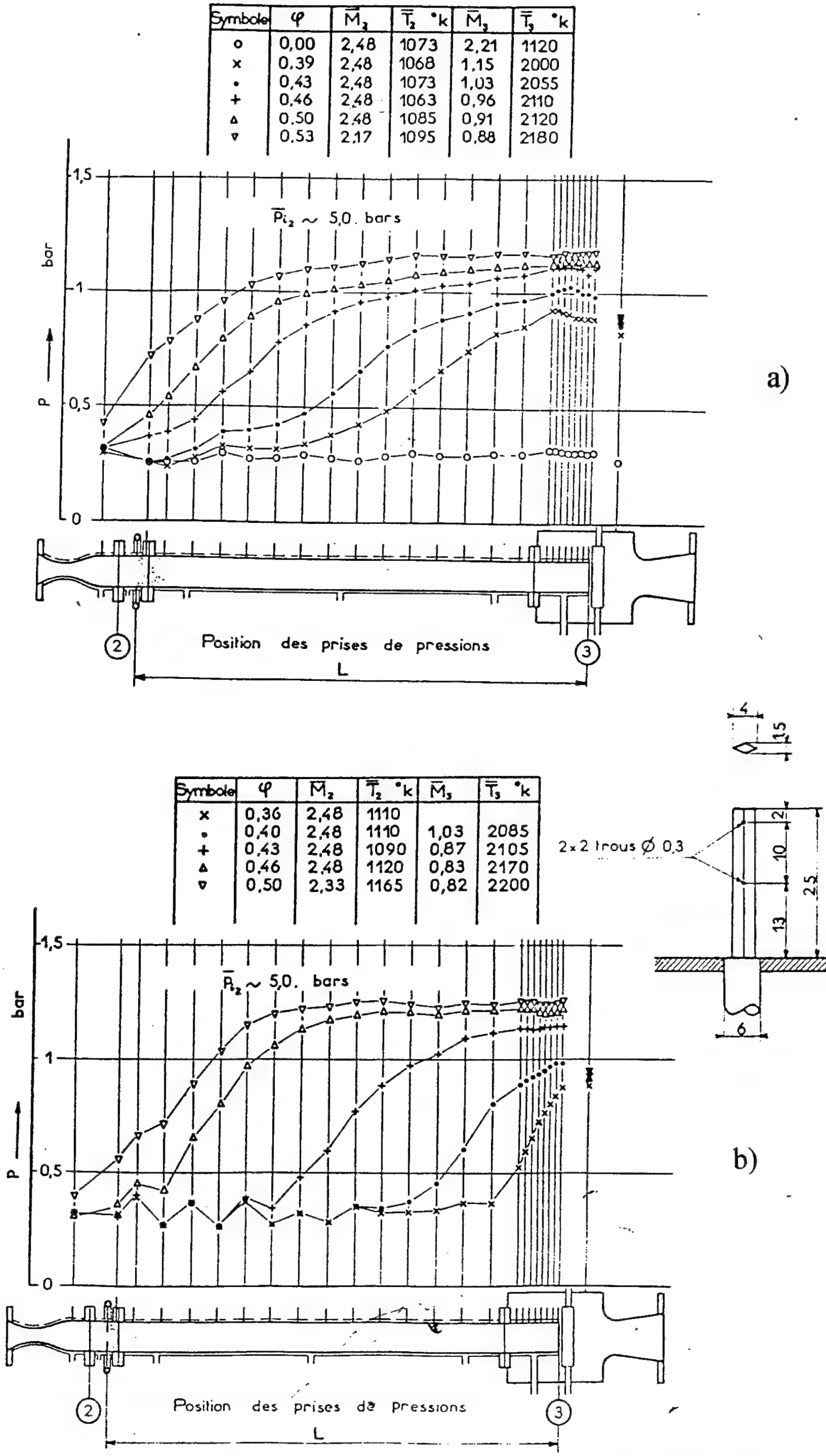


Fig. 1.2. Unit scheme.
1 – repeat air heating; 2 – air; 3 – oxigen; 4 – kerosene; 5 – water; 6 – pressure; 7 – supersonic nozzle; 8 – diffuser.



a)

Symbole	φ	$\bar{M}_2$	$\bar{T}_2$ °k	$\bar{M}_3$	$\bar{T}_3$ °k
o	0,00	2,48	1073	2,21	1120
x	0,39	2,48	1068	1,15	2000
•	0,43	2,48	1073	1,03	2055
+	0,46	2,48	1063	0,96	2110
Δ	0,50	2,48	1085	0,91	2120
∇	0,53	2,17	1095	0,88	2180

b)

Symbole	φ	$\bar{M}_2$	$\bar{T}_2$ °k	$\bar{M}_3$	$\bar{T}_3$ °k
x	0,36	2,48	1110		
•	0,40	2,48	1110	1,03	2085
+	0,43	2,48	1090	0,87	2105
Δ	0,46	2,48	1120	0,83	2170
∇	0,50	2,33	1165	0,82	2200

Fig. 1.3. Static pressure distribution in cylindrical combustor with length L = 0.77 m for wall injection (a) and strut injection (b).

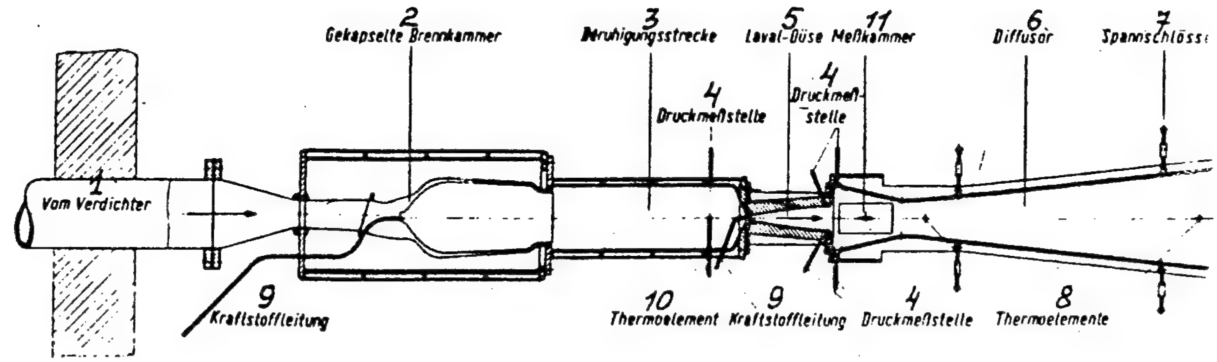
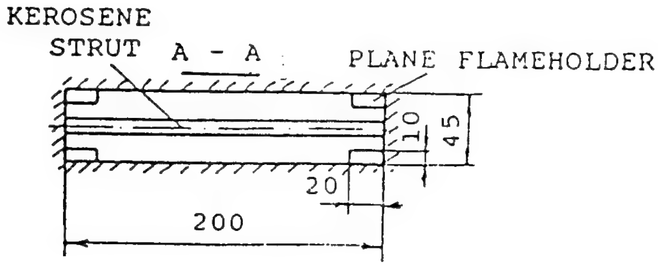
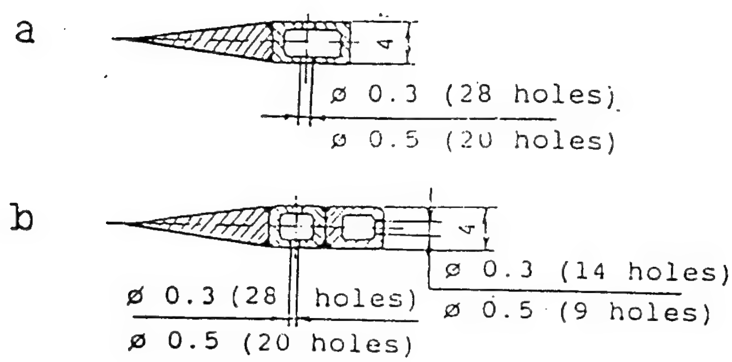


Fig. 1.4. Wind tunnel for investigation of supersonic combustion (air flow rate equal to 2 kg/s).
1 – from compressor; 2 – combustion chamber cowl; 3 – fore-chamber; 4 – pressure measuring heads; 5 – supersonic nozzle; 6 – diffuser; 7 – coupling nut; 8 – thermocouples; 9 – fuel pipe; 10 – thermocouple; 11 – working section.



Schemes of combustors with one-row kerosene injector



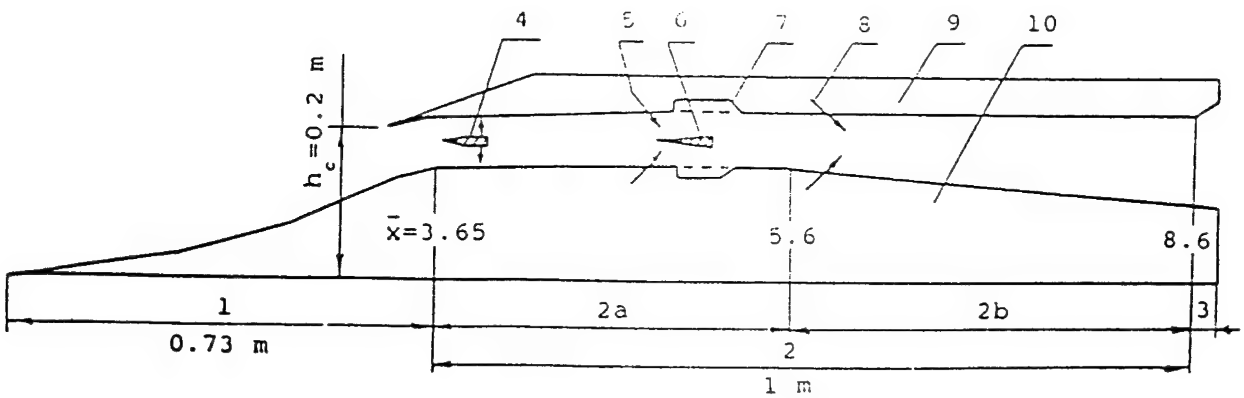


Fig. 1.5. Scheme of the investigated 2-D model Scramjet and scheme of kerosene injectors.
1 – inlet; 2 – combustor ; 3 - nozzle; 4 – kerosene injector; 5, 8 – hydrogen injector; 6 – hydrog^n strut stabilizer; 7 – niche flameholder; 9, 10 – outer cowl, bottom wall.

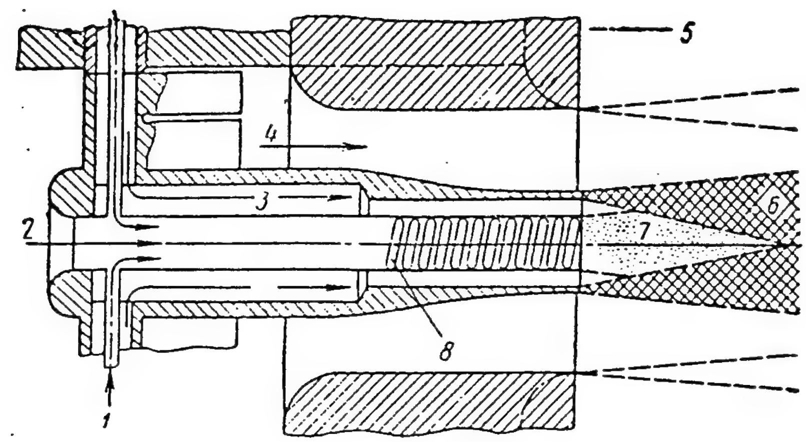


Fig. 1.6. General layout of fuel injector for flame holding in subsonic and supersonic air flow.
1 – pilot hydrogen flow; 2 – pilot air flow; 3 – main fuel flow; 4 – main air flow; 5 – outer part of supersonic nozzle; 6 – fuel-air mixture; 7 – combustion products; 8 – catalyst (platinum).

2. PROBLEM STATEMENT OF A OF EXPERIMENTAL INVESTIGATION

The review given in chapter 1 is devoted to in of autoignition of liquid le in the air flow at various flow parameters and various characteristics of spayed fuel. In spite of certain deviations the majority of experiments confirm the well-known dependence first proposed by B.Mullins. This dependence determine induction time in the wide range of parameters basically according to temperature and pressure of windward air flow:

$$\tau_i = 10^{-10}\, P^{-1} \exp(20634 / T),$$

where τ – s, P – kg/sm^2, T – K.

It is necessary to stress that there is no pure experiment on kerosene autoignition in the supersonic flow without disturbances by shock wave or stall zones.

We should also point out that there are some data according to that ignition delay time show a considerable discrepancy with data of Mullins. For example at certain values of P and T kerosene ignition delay time is increasing (see, for example, fig. 2.1, data of A.Mestre for rich mixtures [10] and data of H.Wolfer for diesels [11]).

We suppose that such disagreement can be related with quality of liquid fuel spraying as well as with difference in local turbulence parameters of the flow in the point where reaction starts. These new factors can have an additional influence on parameters of kerosene ignition in the supersonic flow.

It is known that then kerosene is injected into supersonic flow size of sprayed drops considerably increases due to big difference between speeds of the flow of the kerosene jet (see for example data of [20]). At the same time turbulence performances of supersonic flow transfer impair, and first of all due to turbulence pulsations [21]. We presume that both these factors are to improve kerosene ignition in comparison with subsonic ignition, although due to high

speeds to obtain necessary parameters the ignition require higher temperature of air flow.

From the other point there is a study [22] devoted to evaluation of influence of fuel evaporation upon ignition delay time. This study using certain simplifying conditions shows that to determine how evaporation influences on the ignition delay it is necessary to compare time of drop evaporation τ_u and time of ignition delay τ_i. If $\tau_i > \tau_u$ then parameters of ignition of two-phase mixture practically coincide with parameters of homogeneous mixture ignition (there is only a slight increase of τ_i due to decrease of environment temperature caused by heat lost for fuel evaporation).

At $\tau_i < \tau_u$ that can be observed at higher temperature of the air flow, the mechanism of autoignition changes. In these conditions ignition delay time is determined by evaporation time.

Therefore the usual dependencies for ignition delay will have another form. For example τ_i as well as constant of drop evaporation will be a week function of pressure and weaker then exp(E/ (RT)) from the temperature. Formally it is possible to interpret as change of activation energy E.

Thus, the authors suppose that the new data on the kerosene ignition can be obtained at the test unit providing one of the following conditions: if $\tau_i > \tau_u$ or $\tau_i < \tau_u$.

Besides it is necessary that for all possible test conditions the fuel system does not introduce any disturbances into the supersonic flow. If for evaluation purposes we take evaporation constant τ_u as equal to constant of combustion of individual drops (that is possible because of high temperature of surrounding air flow)

$\tau_u = d_o^2 / K$, where $K \approx 0.9\ mm^2/s$,

then evaluation leads to conclusion that if drop diameter $d_o = 20\ \mu m$ the condition $\tau_i \geq \tau_u$ is effective for the supersonic flow having $M_a = 2$, $T_a^* \approx 2000$

K. At the same time $d_o = 100$ μm and at subsonic flow speed ($M \approx 0.4$) the condition is $\tau_i < \tau_u$.

Thus comparison study of kerosene combustion in subsonic and supersonic flows will help to define the real influence of such factors as evaporation and temperature parameters on the kerosene ignition delay in the air.

The processing of experimental results could help to determine how the mentioned parameters influence the ignition delay.

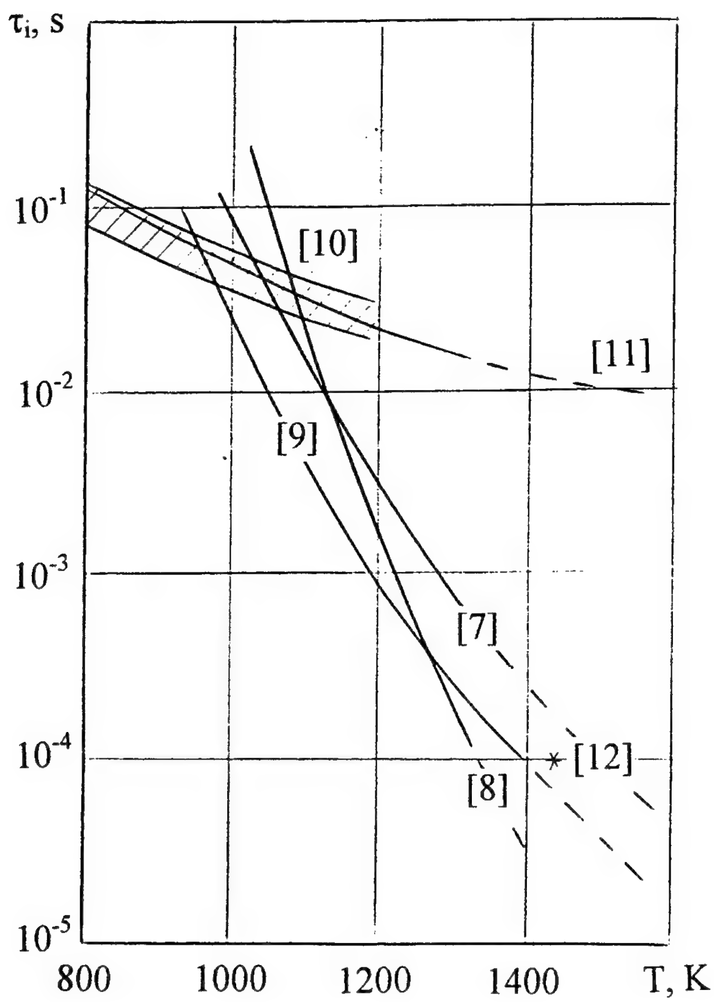


Fig. 2.1 Induction time comparison for various authors.

3. EXPERIMENTAL TEST-BENCH AND SUBSTANTIATION OF CHOICE OF ITS BASIC PARAMETERS

3.1. Test-bench design

The principal scheme of the test-bench which could allow to carry out a comparative investigation of kerosene ignition under condition of its injection by the same injection system into subsonic and supersonic flows ignition delay given on fig 3.1. Its detailed description can be found in the study [2].

The test bench consists of the following units:

- air pipeline with flow rate G_a,
- air heater operating on kerosene with flow rate G_{fh},
- oxygen system with flow rate G_{O2},
- system of kerosene injection into the main combustion chamber G_{fi}. Kerosene can be injected into subsonic (A) and supersonic (B) parts of the test-bench.

To avoid disturbances of supersonic gas flow, fuel is injected into supersonic part of the test-bench through pipe injector inserted through the supersonic nozzle.

The supersonic nozzle where subsonic flow is accelerated up to supersonic speeds divides subsonic part of the test-bench from the supersonic one. At the supersonic part there is a window allowing controlling appearance of the flame visually.

Oxygen injected into the chamber is to recover oxygen concentration in the combustion products of the heater equal to the air ($G_{O2} = L_o\, G_{fh}$). At oxygen flow rate more or less then that, oxygen concentration in the combustion products in front of the nozzle will differ from oxygen concentration in the air.

To prevent choking of the supersonic flow the outlet part of the test-bench right behind the window is designed as a widening channel.

Placing the fuel injector into positions A or B (or another one) and changing temperature of combustion products it is possible to determine the conditions in which kerosene ignition can be observed through the window and then find ignition delay for two different points of fuel injection.

Below Indices A and B are used to denote parameters of subsonic and supersonic flows accordingly.

It is obvious that supersonic ignition can be observed only at significantly higher level of flow temperatures.

The following comparison of ignition delay times τ_a and τ_b in the integrated coordinates ($lg(\tau)$, $1/T$) will allow to determine influence of spraying and flow parameters on autoignition.

In the proposed test-bench in both cases (injection into subsonic part or injection into supersonic part) the initial stages of ignition will take place at the varying flow speed (the speed will change from subsonic in the beginning and will rise to supersonic). It should be stressed that this case simulated ignition conditions then fuel is injected into stall zone (subsonic zone) of the supersonic flow, and thus has a practical value. Besides on the base of such scheme it is possible to design injector-burner of a type studied in the work [18].

3.2. Measurement methods and equipment

During experimental investigations we measured air, oxygen, main and supplementary fuel rates, gas temperature at the outlet of the supplementary combustion chamber and at the outlet of the last section.

Fig. 3.6 gives the scheme of the experimental test-bench showing cross sections where parameters are measured as well as the parameters themselves. The detailed description is given in the section 2 of the second report.

The figure uses the following notation:

T^* - total temperature;

P^* - total pressure;

P - static pressure;

ΔP - pressure difference at the measuring spacer;

f - rotation frequency of the fuel consumption gauge.

Air and oxygen flow rates are determined using measuring spacer by calculations on the base of measurements of the total pressure in front of the measuring spacer, pressure difference and flow temperature.

Fuel flow rates at the main and supplementary combustion chambers are determined by turbine flow rate meters (light turbines installed at the fuel pipes). The turbines rotate with frequency proportional to the volumetric fuel flow rate. The rotation frequency is measured allowing determining of flow rate according to calibration dependencies. Rotation frequency is registered by frequency meter via inductive circuit.

To measure temperature the chromel-aluminium (220-1570 K) and W + 5% Pe - W + 20% Re (270 - 2770 K) thermocouples are used. The thermocouples readings are registered by millivoltmeters.

Pressure is registered by reference and electric manometers.

Pressure difference at the measuring spacer is read by electric differential manometer.

The autoignition process at the main combustion chamber can be observed through a transparent quarts wall and is filmed by a video camera.

3.3. Choice of the test-bench parameters

The main parameters of gas flow are its temperature and pressure. For the calculations below the approximation dependence for gas flow temperature after the heater was used.

Fig. 3.2 represents the parameters for the total temperature at the initial values of air temperature $T_a = 300...900$ K and at various air excess coefficients in the heater α_h ($\alpha_h = G_a / L_o G_{fh}$).

It is clear that the temperature of gas in the heater is determined by value of α_h. It is assumed that fuel in the heater with flow rate G_{fh} burns out completely.

Injection of additional oxygen will decrease to a certain extent flow temperature shown on the fig. 3.2.

Varying α_h and, therefore, gas temperature it is possible to change ignition delay for the both points of fuel injection (A and B).

Fig. 3.3 represents variation of logarithms of ignition length X_1 and X_2 (in meters), calculated by the following dependencies:

$X_1 = \log (U_1 \tau_I (P_1, T_1))$,

$X_2 = \log (U_2 \tau_I (P_2, T_2))$,

the test-bench parameters: $M_a \approx 2$, $P_1^* = P_2^* = 6$ at in the points A and B.

Ignition delay time was calculated by Mullins dependencies.

$\tau_I = 10^{-10} P^{-1} \exp (20634 / T)$.

where τ_i – s; P – kg/sm^2 ; T – K.

For example, at $\alpha_h = 3$; $T_1^* = T_2^* = 1148$ K

for the variant A: $P_1 = 5.4\ 10^5$ Pa, $U_1 = 247$ m/s, $T_1 = 1123$ K;

for the variant B: $P_2 = 0.86\ 10^5$ Pa, $U_2 = 1012$ m/s, $T_2 = 726$ K.

At the described test-bench it is possible to obtain ignition length less then 1 m ($X_1, X_2 < 0$):

for the variant A at $\alpha_h \leq 3{,}3$;

for the variant B at $\alpha_h \leq 1{,}3...1{,}4$.

If the total length of the test-bench is about 1 m then for the studied conditions to obtain ignition in the supersonic flow the gas heater have to operate on the rather rich mixture ($\alpha_h \leq 1{,}3...1{,}4$), i.e. at $T_1^* \geq 2000$ K.

For the modes with kerosene injection into the subsonic part ignition can be obtained much easier $\alpha_h \leq 3.3$ and $T_1^* \geq 1000$ K.

Evaluation of evaporation length ($L_u = U \tau_u$) proved that this length corresponds to lg $L_u \approx 0{,}4\ldots1{,}2$ (at $d_o = 100$ μm); lg $L_u \approx -0{,}2\ldots-1$ (at $d_o = 20$ μm).

So the condition $\tau_I < \tau_u$ corresponds to the variant A, and the condition $\tau_I > \tau_u$ – to the variant B.

Thus in the proposed scheme fuel injection into subsonic flow can lead new effects and fuel injection into supersonic flow have to follow the usual dependencies.

It is necessary to stress though that to obtain relatively big drops during fuel injection in the point A the diameter if injector outlet nozzle has to be 1 mm, but if fuel is injected into supersonic flow (point B) from the same injector with the same nozzle size the diameter of kerosene drops is less and is estimated as approximately 10 μm [23].

It is clear that it is better to carry out study of autoignition with additional gas oxidizing and at relatively low flow rates of the main fuel, because its larger amount will lead to the losses for heating and evaporation of the fuel and will worsen the ignition conditions.

The minimal flow disturbances can be obtained using small-sized tubular injectors. On the other hand with tubular injector decrease of flow rate of fuel injected into the flow will cause over-heating of the injector walls.

If we allow formal value of air excess coefficient for the fuel injected into the flow $\alpha_i = G_a / (L_o G_{fi})$, then the efficient air excess coefficient at the back-part of the chamber α_{ef} can be calculated from α_i, α_h and β:

$$\alpha_{ef} = \frac{G_a - L_o G_{fh} + G_{o2} / 0.23}{L_o G_{fi}} = \frac{(\alpha_h - 1 + \beta)}{\alpha_h} \alpha_i ,$$

where $\alpha_h = G_a / (L_o G_{fh})$; $\alpha_i = G_a / (L_o G_{fi})$.

Ratio the flow rate of oxygen injected into the chamber to oxygen theoretically necessary for the complete compensation:

$\beta = G_{o2} / (0.23 L_o G_{fh})$,

where L_o – stoichiometric coefficient of kerosene for the air,

0.23 – oxygen fraction in the air.

At $\beta = 1$ we receive $\alpha_{ef} = (\alpha_h - 1)\, \alpha_i / \alpha_h$.

Fig. 3.4 represents variation of α_{ef} (if no oxygen is injected $\beta = 0$) for the function α_h at α_i =2 and 6.

As we see at $\alpha_i = 6$ and $\alpha_h \leq 1{,}3...1{,}4$ (that is important in case of injection into the supersonic flow) value α_{ef} remains $\alpha_{ef} \leq 2$. We suppose that is quite enough for study of autoignition. For subsonic modes (at $\alpha_h \leq 3{,}3$) and at the same values of $\alpha_i = 6$ the effective air excess coefficient will be higher ($\alpha_{ef} \leq 5$).

That is why changing additional oxygen injection it is possible to receive the save value of α_{ef} at various α_h.

Nevertheless the evaluation shows that for the father evaluation of thermal state of the injector the value of $\alpha_i \approx 6$ can be accepted as the maximum limit for the minimal flow rate of kerosene.

If kerosene is in into the chamber by non-cooled injector made as L-shaped tube the outlet of which is placed in the center of the channel and is directed windward, then in the studied conditions especially for the kerosene injected into supersonic flow of high temperature (T = 2000 K) the thermal parameters of such injector can cause a problem.

If assume that the chamber channel is 20 mm in diameter, total pressure of the flow $P^* = 6 \cdot 10^5$ Pa, the nozzle provides Mach number $M \approx 2$ ($\lambda = 1.67$) at the inlet into the main chamber (in front of the nozzle $\lambda = 0.4$) then for various gas temperatures (corresponding to $\alpha_h = 1$; 1.5; 2 and temperatures $T_1^* = 2382$; 1818; 1495 K) it is possible to estimate external temperature of the surface of the injector tube (T_{w1}) facing hot gas.

As an injector tube it is possible to use a tube of stainless steel 2 × 1 mm in cross-section. As a determining parameter we took air excess coefficient for kerosene injected through the tube was (initial kerosene temperature was assumed equal to 300 K).

The longitudinal subsonic flow over the tube was considered. The calculation was carried out with regard to the radiation from the tube walls.

At the studied parameters ($T^* = 1495...2383$ K; $P^* = 6 \cdot 10^5$ Pa) air flow rate in the chamber is $G_a = 0,103...0,115$ kg/s. Variation of α_i from 2 to 6 corresponds to kerosene flow rate 3,7...1,2 g/s through the injector tube.

The temperature level of injector walls at $T^* = 2383$ K is prohibitively high.

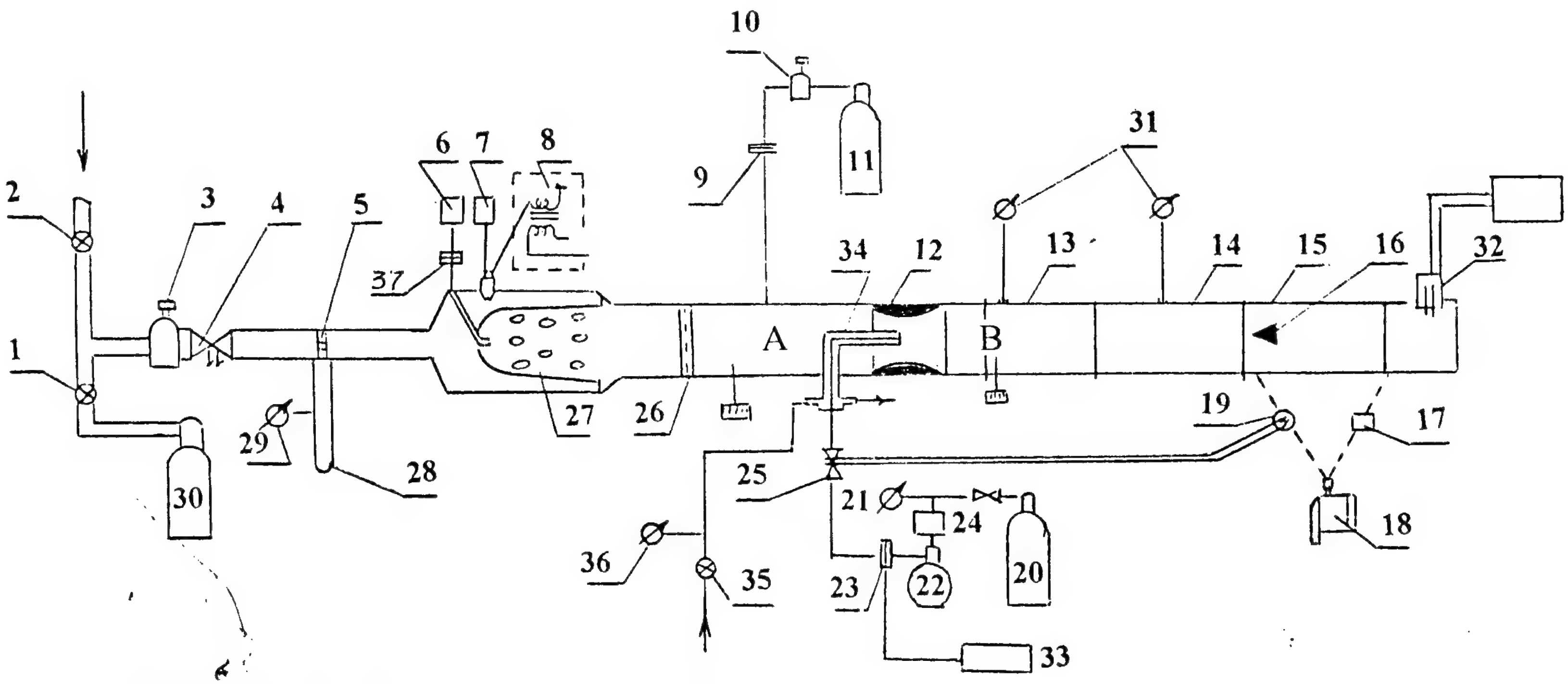
It should be stressed that the calculations are given for the case of turbulent flow node in the kerosene tube that is effective for $\alpha_i \approx 3$. At $\alpha_i > 2$ the Reynolds number (Re) for the current in the tube corresponds to the fillet area of the current. At more precise estimation this could decrease effective heat efficiency of the tube and increase of the wall temperature for 150...200 K more at $\alpha_i = 6$. In this case the tube of even small diameter would be preferable, for example 1 $\times$ 0.5 or 1.5 $\times$ 0.7 mm.

Thus if jet tubes are used for the supersonic ignition which requires higher flow temperatures ($T^* \approx 2000$ K) even short-term tests require sufficient kerosene flow rate $G_{ft} \geq 4$ g/s ($\alpha \leq 2$).

In these conditions at $\beta = 0$ the value of α_{ef} is less ($\alpha_{ef} \approx 0.5$) and it is possible to increase it by additional supply of hydrogen.

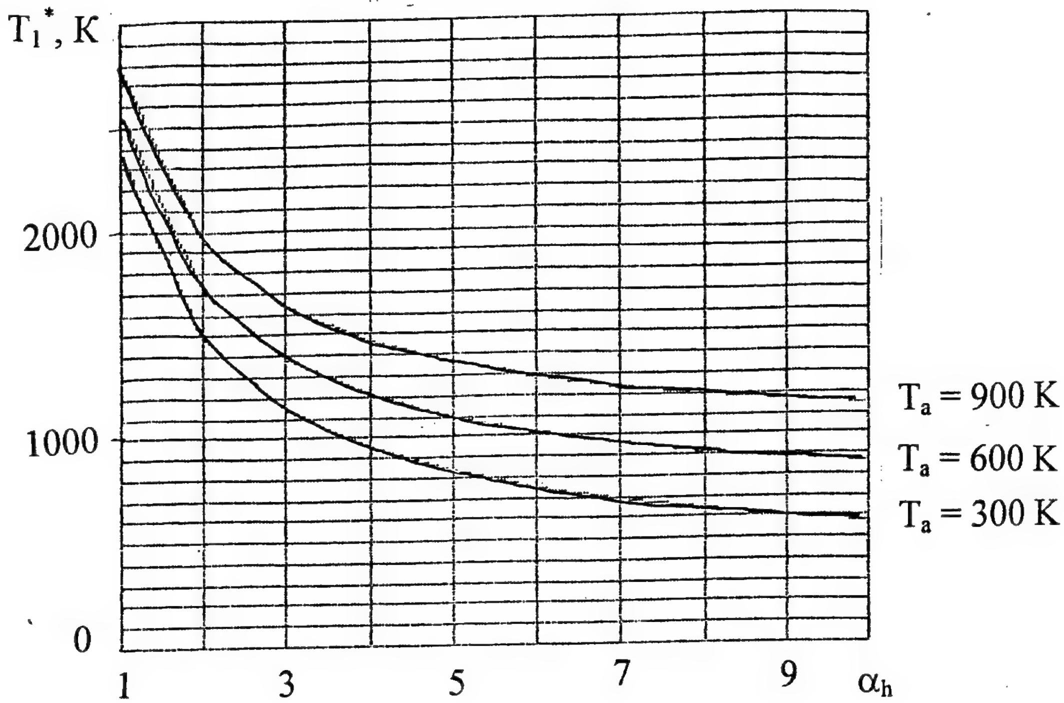
As follows from the above-mentioned formulae $\alpha_{ef} = 1.2$ already at $\beta = 0.5$, $\alpha_h = 1.4$ and $\alpha_i = 2$.

So the cooling requirements set a limit of the minimal kerosene flow rate through the tubular injector which is cooled by kerosene flowing inside. For the tube and the mentioned flow parameters this flow rate corresponds to $\alpha_i \approx 2$ ($G_{ft} \approx 4$ g/s).



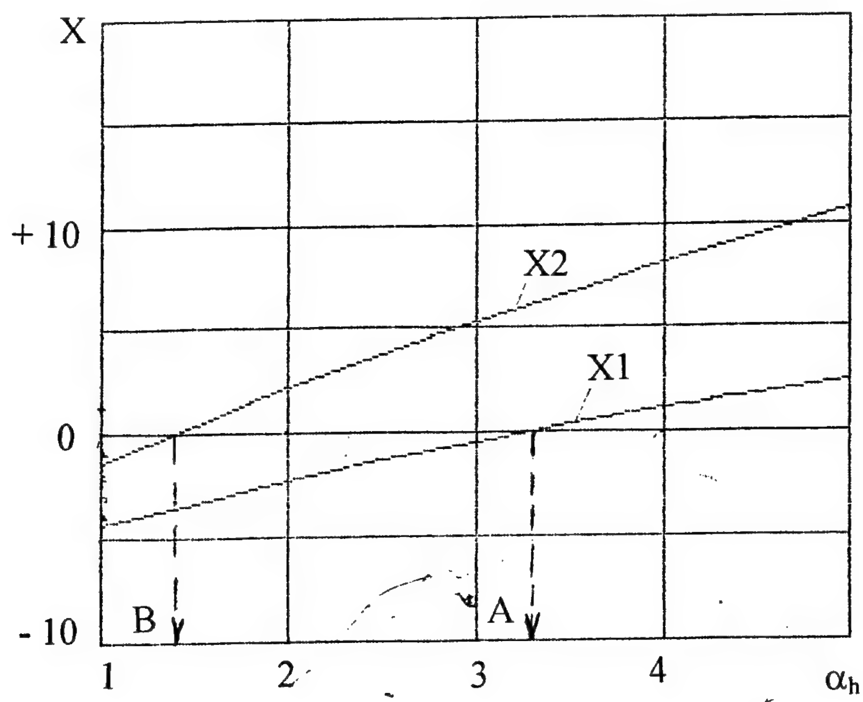
1. Valve of air pipe-line
2. Valve of cylinder
3. Air reducer
4. Air electrovalve
5. Measuring spacer of air-flow rate
6. Fuel pump of heating chamber
7. Fuel pump of ignitor
8. Ignition chamber
9. Oxygen flow rate measuring spacer
10. Oxygen reducer
11. Oxygen cylinder
12. Laval nozzle
13. Working section
14. Measuring section
15. Main combustion chamber
16. Flame holder
17. Timer
18. Video camera
19. Signal bulb
20. Cylinder of pressurization
21. Pressure manometer
22. Fuel cylinder
23. Fuel flow rate gauge
24. Fuel; reducer
25. Fuel electrovalve
26. Protective grid
27. Supplementary combustion chamber
28. Differential manometer
29. Manometer
30. Air cylinder
31. Static pressure manometer
32. Ionization gauge
33. Frequency gauge
34. Ingector with cooling
35. Cock of water cooling
36. Water manometer
37. Fuel flow rate gauge

Fig. 3.1.



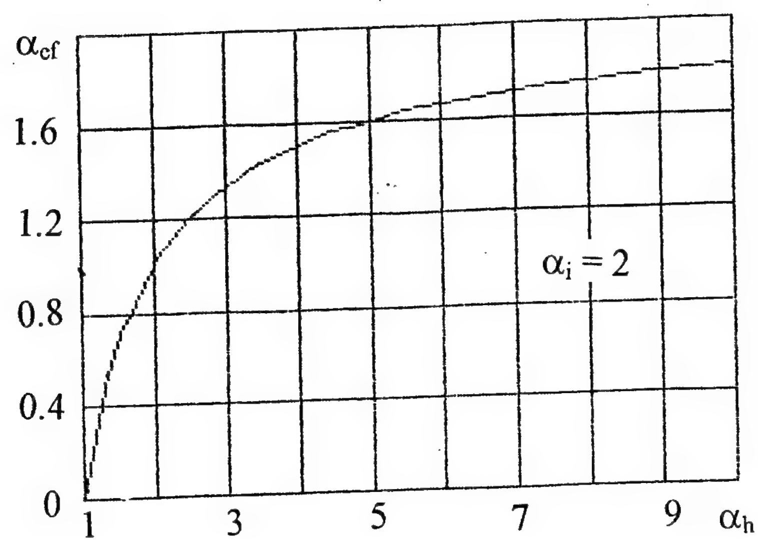
T_1^*, K
2000
1000
0
1
3
5
7
9
α_h
T_a = 900 K
T_a = 600 K
T_a = 300 K

Fig. 3.2.



X
+ 10
0
- 10
X2
X1
B
A
1
2
3
4
α_h

Fig. 3.3.


α_{cf}
1.6
1.2
0.8
0.4
0
$\alpha_i = 2$
1
3
5
7
9
α_h

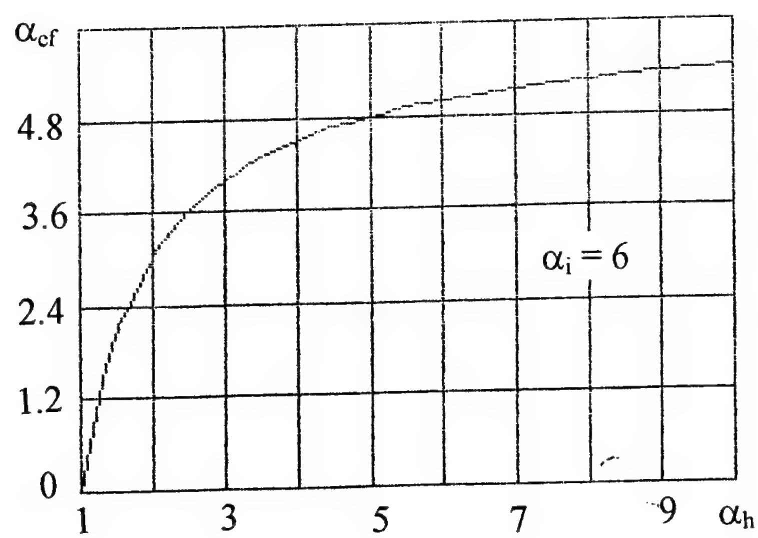
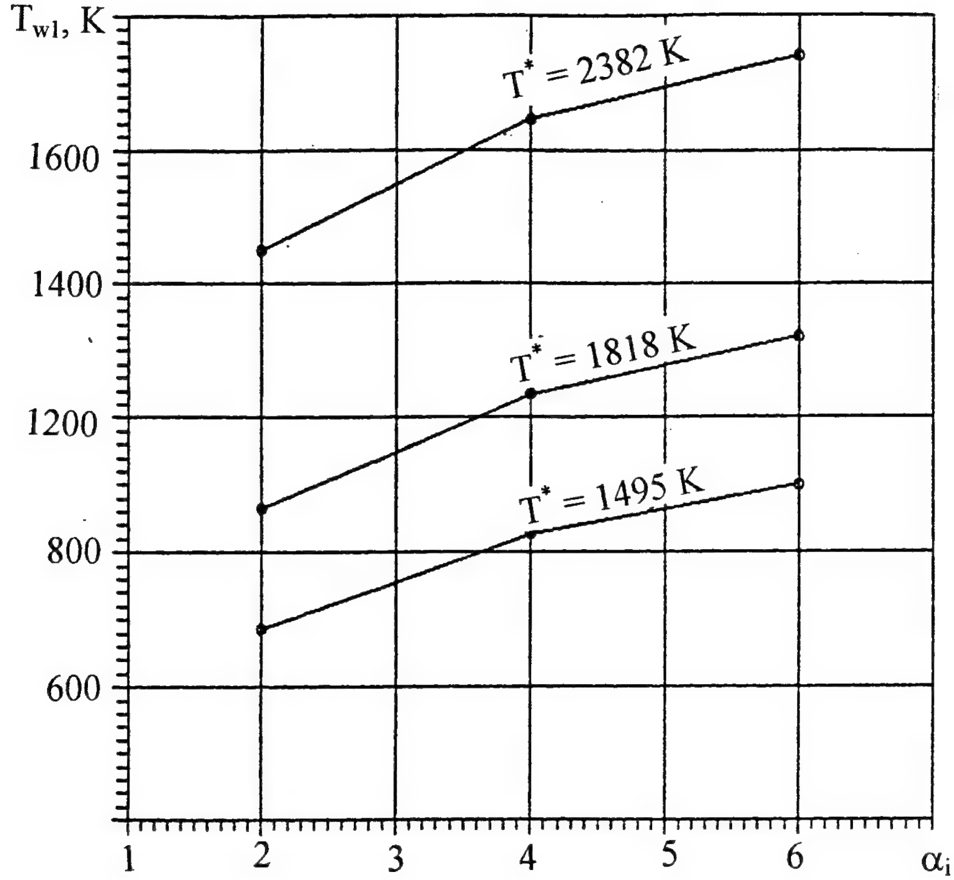

α_{cf}
4.8
3.6
2.4
1.2
0
$\alpha_i = 6$
1
3
5
7
9
α_h

Fig. 3.4



T_{wl}, K
1600
1400
1200
800
600
1
2
3
4
5
6
α_i
$T^* = 2382$ K
$T^* = 1818$ K
$T^* = 1495$ K

Fig. 3.5

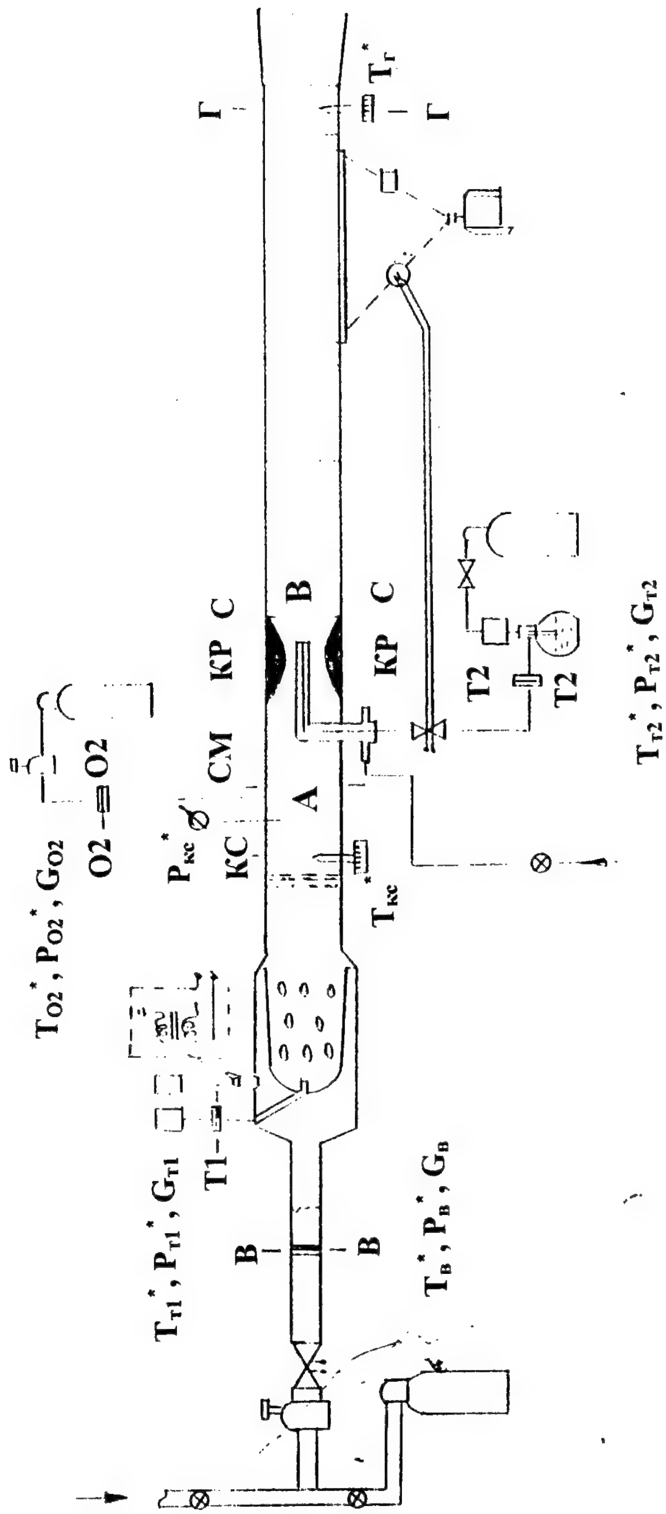


Fig. 3.6

4. RESULTS OF EXPERIMENTAL INVESTIGATION

The main purpose of this work is investigation of process of kerosene autoignition in the supersonic flow.

The scheme of the test-bench is given on the fig. 3.1 and described above in the section 3.1.

Air was heated in the supplementary combustion chamber (heater) be burning kerosene TC-1. During the experiments temperature in the heater changed in the wide range $T_{\kappa c}^{*}$ = 1400...2000 K. Early experiments had shown that gas combustion efficiency at the chamber outlet is not lower $\eta = 0.9$.

The test-bench allows compensating lack of oxygen, caused by burning in the heater, by additional oxygen from a tank. But in the tests that have been carried out additional oxygen was not used because of the short test time.

Experimental investigation has been carried out at three different values of supersonic flow speed. This variation was achieved by Laval nozzles (item 12, fig. 3.1) with various bottlenecks.

The main combustion chamber also used aviation kerosene TC-1 fed by injector.

The test-bench allowed installation of water-cooled injector, but due to it large size such injector causes considerable disturbances into the passing gas flow. That is why in the present short-time tests we used non-cooled injector (a bent tube with its outlet in the center of the channel and directed downstream). The tube is of stainless steel with inside diameter d = 1 mm and wall thickness $\delta = 0.5$ mm. Injector of such design sets a certain limits on the minimal kerosene flow rate in the main combustion chamber as the injector is cooled by the kerosene which flows through it.

The test-bench allows moving the fuel injector along the axis, so kerosene can be injected either into subsonic or into supersonic part of the nozzle. In the present set of tests kerosene was injected into supersonic part of the nozzle.

Behind the nozzle there were two spacers made of a pipe with inside diameter d = 20 mm (item 12, fig 3.1, length L = 200 mm and item 14, fig. 3.1, length L = 120 mm) and so-called main combustion chamber with transparent wall (item 15, fig. 3.1, length L = 300 mm, diameter d= 20 mm).

Methods of measurements and equipment used for the experimental investigations are described in the section 3.2.

The methods of each experiment were carefully planed. The necessary parameters of the working bodies for each test were calculated according to the methods of experimental data processing given in the section 3 of [2]. That is why the total time of "hot" experiment was τ = 10...15 s.

An experiment started from setting of air parameters. Then the supplementary combustion chamber (the heater) was started and gas temperature after the heated increased up to $T_{кс}^* \approx 700$ K. Then we simultaneously increased fuel fed into the heater and started to feed fuel into the main combustion chamber. Necessary flow rates had been calculated in advance.

During the preliminary tests described in the section 4.1 the main combustion chamber was equipped with a flameholder (item 16, fig. 3.1).

All the main experimental investigations of kerosene autoignition in the supersonic flow have been carried out without any supplementary flameholders.

When fuel is injected into high-temperature gas flow with specific parameters in a certain distance from the point of injection fuel mixture autoignites and luminescence appears. The distance between point of fuel injection and flame front (length of the "cool" area) is determined be flow speed and time of autoignition delay, which depends on the flow parameters.

The methodology has a serious influence on accuracy and authenticity of the experimental investigation results. The autoignition process is very sensitive to the parameter fluctuations, which are inevitable in the real conditions. It is difficult to determine exactly ignition delay time as this process develops in several stages beginning with slight blue luminescence to the stable flame front.

The limits of autoignition were set as the flow parameters at which fuel blazed up in the section with transparent quartz side wall (item 15, fig. 3.1); the flame outbreak was registered visually. The results of a certain test were used for the farther investigation only of gas flow temperature in front of the nozzle was not equal to the temperature at the outlet of the main combustion chamber ($T_{г}^{*}$ - $T_{кс}^{*}$). These temperatures were read by thermocouples W + 5% Re – W + 20% Re (270 – 2770 K)

For the studies of autoignition in the subsonic flow, gas was heated be electric heater, the tests used ionization detector accurately sharply reacting to the mixture ignition. For the tests in the supersonic flow gas was heated by fuel burning in the supplementary combustion chamber, so it was impossible to use ionization detector (item 32, fig. 3.1) due to active zones caused by combustion process in the heater.

4.1. Preliminary tests

It is difficult to organize kerosene combustion in the supersonic flow in the channel.

On the first stage of the preliminary tests at relatively low temperatures of gas flow ($T_{кс}^{*}$ = 1000...1100 K) the acoustic waves registered. Supposedly in these test combustion was too far from injection point and it was impossible to detect it visually.

On the second stage of preliminary tests the ignition was initiated by flameholder (a non-streamline body) placed into the flow in the main combustion chamber. The edge angle of the flameholder $\varpi = 10°$.

This allowed precise determination of ignition time, as its characteristic feature is appearance of combustion behind the flameholder. Results of one of such experiments are given in the section 5 of [2].

The main purpose of preliminary tests was to adjust system of measurements and experimental methods.

Comparing the results of preliminary tests, which used a flameholder, with results of the main tests and basing on the analysis of [12,13,15] it is possible to make the following conclusion: if there is a flameholder or shock wave system, flow ignites at lower temperatures of windward flow. It is caused by increase of the local temperature in the shock waves.

4.2. Dependence of autoignition temperature from flow speed

In the frames of the present contract the test-bench was used for experiments aimed to determine autoignition temperature in case of two-phase mixture at fuel injection into the zone of supersonic speeds.

It should be pointed out that the tests took into consideration the fact that it is necessary to obtain an acceptable ignition delay time, which at supersonic flow speed would allow forming of stable ignition in the distance 350...600 mm from the fuel injector in the section of quartz window, where ignition is registered visually and by video camera.

Time of fuel presence was varied in two ways: by variation of distance from injection point to the point of ignition registration (by removing of spacer 14, fig. 3.1) and by variation of flow speed.

Autoignition temperature was taken as equal to the total temperature of the gas flow in front of the nozzle.

Fig. 4.1 shows dependence of autoignition temperature T_s from the flow speed M at distance between point of fuel injection and ignition point ≤ 600 mm.

The author have carried out experimental investigations at three different values of supersonic flow speed M = 1.2; 1.6; 2.0. Tests for different speeds were carried out with application of Laval nozzles with different areas of nozzle bottleneck.

On the fig. 4.1 a part of experimental points for the supersonic flow was taken from [5] and [13].

The same figure also gives autoignition point for the subsonic flow obtained by the author.

At increase of flow speed from M = 1 to M = 2.5 the limits on the distance from the injection point and ignition point force to increase autoignition

temperature in the range T_s ~1400...2000 K. This dependence can be approximated by the general formula.

Thus, fig. 4.1 generalizes data on the kerosene autoignition temperature for the speed range M = 0,5...2,5.

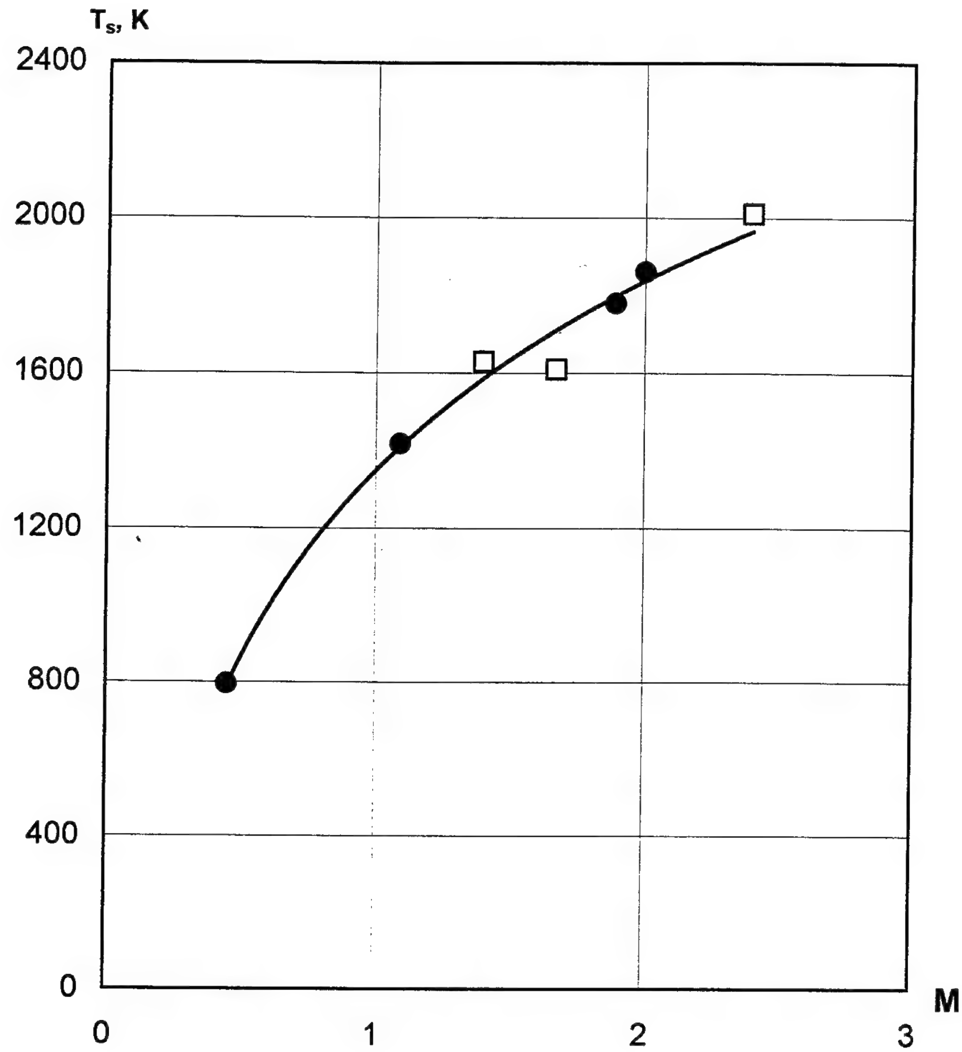


Fig. 4.1.
Dependence of autoignition temperature on flow speed at L< 600 mm:

● - points obtained by the author;
□ - points given in [5, 13].

4.3. Dependence of flow temperature on autoignition delay

Results of experimental investigations of kerosene autoignition at the supersonic flow can be presented as dependence of autoignition delay time from ignition temperature.

During the tests we measured the distance between injection cross-section and autoignition cross-section $L_в$. Time of autoignition delay was calculated from formula:

$\tau_i = L_в / W_c$,

where τ_i , s; $L_в$,m; speed of the gas flow in the cross-section C:

$W_c = \lambda_c (2k_{CM} R_{CM} T_{CM}^* / (k_{CM} + 1))^{0.5}$, m/s.

Processing of the experimental data in the form $\lg \tau_i = f(10^3/T_s)$ is given on fig. 4.2.

Minimal temperature of kerosene autoignition in the supersonic flow T_s = 1420 K has been obtained at M = 1.2.

The same figure shows dependence $\lg \tau_i = f(10^3/T_s)$ received in experimental investigation of Mullins for kerosene autoignition in the subsonic flow (solid line) [7]. It is extended for the higher temperatures (dotted line) which can correspond to the supersonic flow speeds.

The paper [12] shows that ignition of liquid kerosene takes place behind the normal shock wave in the supersonic flow in ~ 150 mm from the point of kerosene injection (M = 2.4; T_a^* = 1200...1500 K; P_a^* = 3.5 bar (P_a = 0.23 бар). The results of processing of data given in this paper on the air parameters behind the oblique shock wave show that ignition delay time of this paper are in good agreement with Mullins data. Disturbances (shock waves) considerably decrease temperature level necessary for kerosene ignition.

With temperature decrease all the points corresponding to different supersonic flow speeds are on the same curve. Thus, the higher flow temperature, the less autoignition delay time depends on speed.

All experimental points are on the curve, which is higher then extended Mullins dependence. It means that autoignition delay time for each of the specified temperatures is more than the time determined by Mullins dependence.

As it is shown on the fig. 4.2. in the supersonic flow at corresponding increase of temperature, autoignition delay time is by two orders of magnitude lower than in the subsonic flow. This phenomenon can be explained by theory of thermal autoignition.

Theory of thermal autoignition of homogeneous evaporated and two-phase mixture is fully developed in several papers. This theory is proved by a large number of experiments carried out for the subsonic flows.

Autoignition in the supersonic flows has the following characteristic features:

1. Supersonic flow speed in the point of fuel injection causes the phenomenon then at the relative speeds more than $\Delta W = 200$ m/s the fuel jet is almost instantly broken and large drops are sprayed. Thus it is possible to assume that fuel is present in the air flow in the form of small drops $d_o \approx 10...50$ μm.
2. In the supersonic flow there is a high level of flow turbulence $Re = (6...7) \cdot 10^5$ in the place of fuel injection. This leads to intensive mixing of flow and to quick leveling of fuel concentration. That is it is possible to assume that fuel drops evenly spread in the whole volume in a very short time.
3. High level of turbulence also leads to intensive evaporation of drops.

It leads to assumption that fuel ignites according to the diffusion mechanism. These conditions influence first of all on the ignition delay time.

It is possible to presume that ignition delay time includes the following components:

- time of fuel breaking τ_{at},
- time of fuel drop evaporation τ_u,
- time of chemical delay of ignition τ_{ch}.

Fig. 4.3 shows the behavior of temperature from the moment of fuel injection to the moment of its ignition and correspondence between components of ignition delay for various flight speeds: a) subsonic; b) supersonic.

It schematically shows that total ignition delay time for subsonic flow consists of the following variables:

$\tau_{iI} = \tau_{at\,I} + \tau_{u\,I} + \tau_{ch\,I}$.

In the supersonic flow components of autoignition delay time are shorter ($\tau_{at\,II} < \tau_{at\,I}$; $\tau_{u\,II} < \tau_{u\,I}$; $\tau_{ch\,II} \approx \tau_{ch\,I}$), besides, these in the supersonic flow these processes are partly combined, so $\tau_{i\,II} < \tau_{iI}$. That is why the total ignition delay time can be determined only by experiments.

It should be stressed that in the supersonic flow even at a short ignition delay time in the supersonic flow fuel ignites very far from the injection point. For example, for $\tau_i = 0.01$ s this distance is 3.2 m at M = 1 and about 6.4 m at M = 2. On such distance flow can be mixed with cold gases, reaction area can be overcooled and the mixture can go out. That is why it is important to shorten the ignition delay time in the supersonic flow by increase of flow temperature at the combustion chamber inlet.

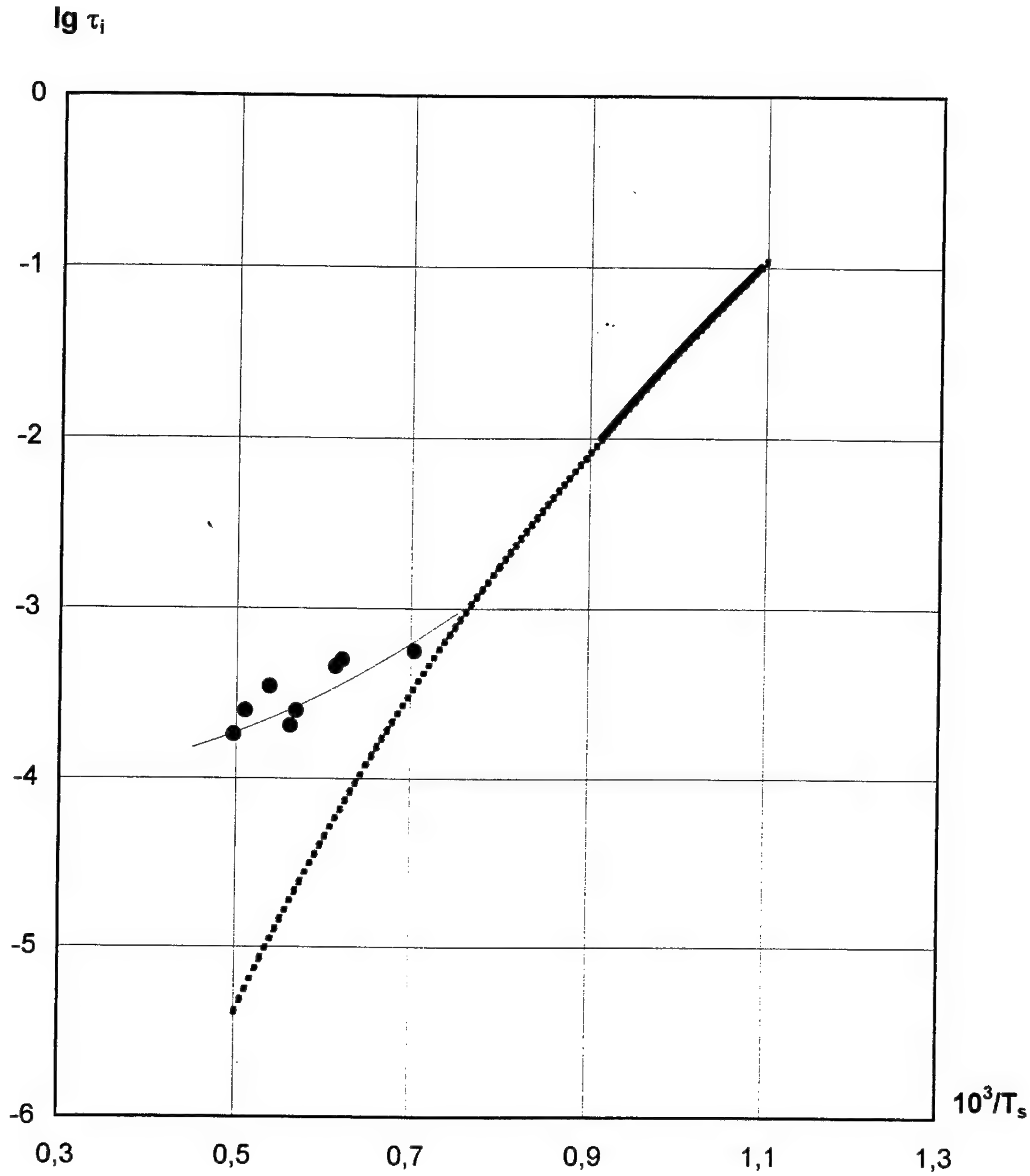


Fig. 4.2.
Dependence of ignition delay time logarithm on value resiprocal of temperature

● experimental points;
·······— Mullins dependence;
— theoretical dependence.

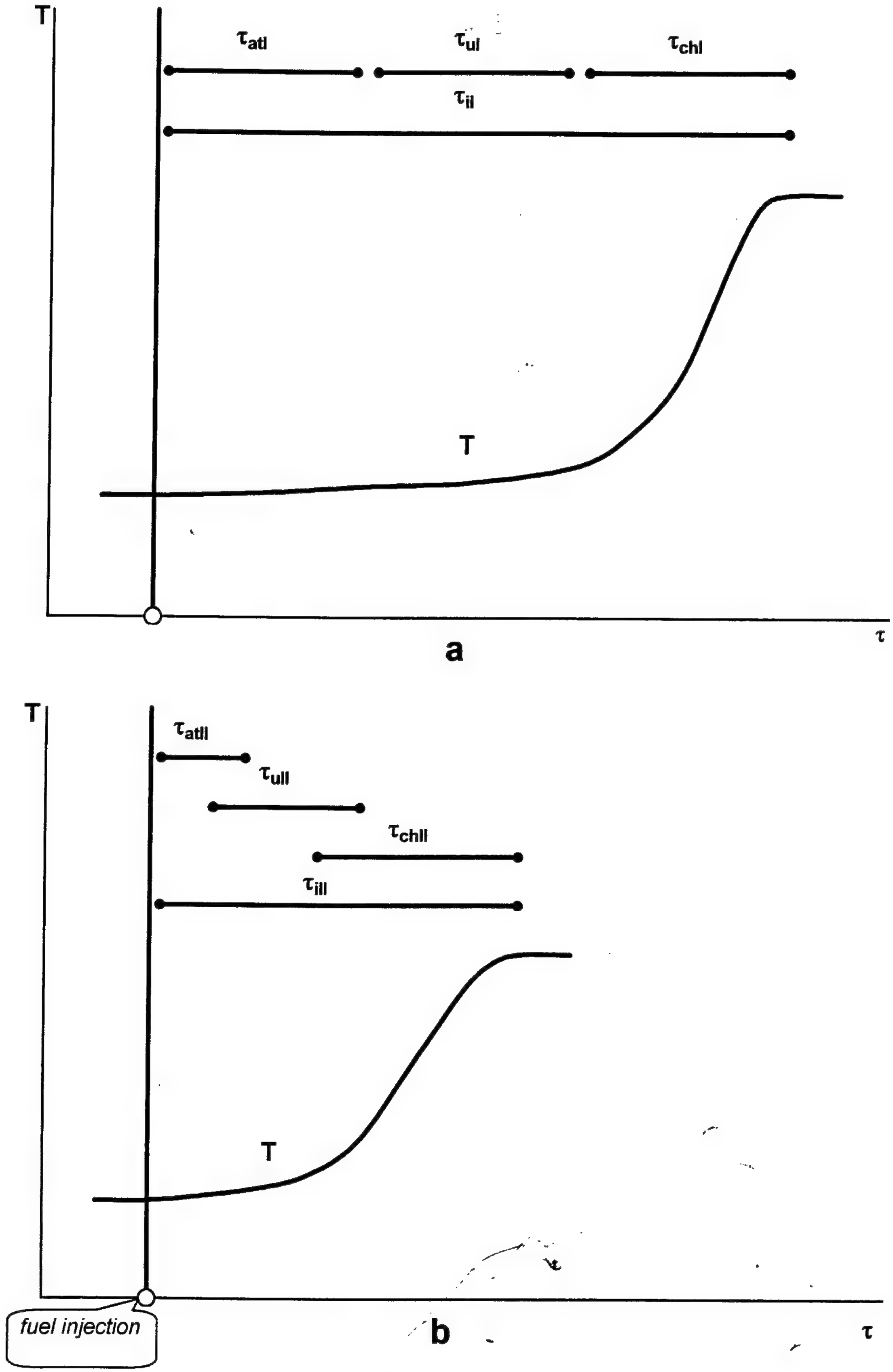


Fig. 4.3.
Diagram of temperature growth from the moment of fuel injection to ignition:
a) subsonic flow;
b) supersonic flow.

4.4 Influence of initial diameter of drops on autoignition delay

Generalization of data given in the paper [22] on the influence of drop size on the autoignition delay time is presented on fig. 4.4.

The calculations were carried out for kerosene-air mixture at P = 1 at air excess coefficient $\alpha = 1.5$ at various diameters of kerosene drops.

The analysis of data presented on this figure gives the following conclusions:

- if lifetime of a drop (evaporation time τ_u) is less or approximately equal to chemical delay of autoignition τ_{ch}, then initial diameter of drops does not influence on the autoignition delay time τ_i;
- if lifetime of drops τ_u is more then τ_{ch}, then τ_i begins to depend on the drop size.

Fig. 4.4 gives not only calculated curves but also experimental data of Mullins from [25]. Changing of average drop diameter from 142 μm to 77 μm for the temperatures at which drops lifetime is less then autoignition delay time does not lead to considerable change of autoignition delay time.

The same figure gives experimental points obtained by the experiments of the present research.

As it was already mentioned, in the supersonic flow, fuel from the injector nozzle is sprayed very intensively and drop size is very small ($d_o \approx 10...50$ μm).

So it is possible to presume that at high flow temperatures, lifetime of drops (τ_u) will be less then chemical time of ignition delay (τ_{ch}). In this case drop diameter does not influence autoignition delay time, i.e. delay time can take the form of dependence 9, similar to dependence 4 on fig. 4.4, but located lower. This location can be explained by particularities of the supersonic flow and high level of temperatures. As a result total autoignition delay time decreases.

4.5. Influence of pressure on autoignition delay time

Fig. 4.5 gives generalized data of the paper [22] on influence of pressure in the subsonic flow on the autoignition delay time. The data are presented in the form of dependence $\lg\tau_i = f(\lg P)$ for two-phase kerosene-air mixture at $\alpha = 1.5$ for various flow temperatures.

As it was already mentioned, in the area of high temperatures at the supersonic flow breaking and evaporation of fuel drops are very intensive and, as we suppose, it is not a limiting process.

Fig. 4.5 shows that at $T_s = 1600$ K, $d_o = 100$ μm and $\alpha = 1.5$, for example, even at a large size of drops pressure increase from P = 1 at to P = 5 at leads to decrease of autoignition delay time from 0.346 ms to 0.289 ms, i.e. only on 17%.

Fig. 4.5 gives not only calculated curves but also experimental points obtained at $T_s = 1173$ K and $d_o = 100$ μm [25]. The experimental points show an agreement with calculated curve 4.

The same figure gives experimental points obtained by the author during investigation of kerosene autoignition in the supersonic flow at $T_s = 1760...1860$ K.

In the supersonic flow at autoignition of kerosene-air mixture total autoignition delay time is considerably lower then in the subsonic flow.

Studying fig. 4.5 it is possible to conclude that the experimental points have a satisfactory degree of compliance with a gently sloping curve. Autoignition delay time practically does not depend on pressure.

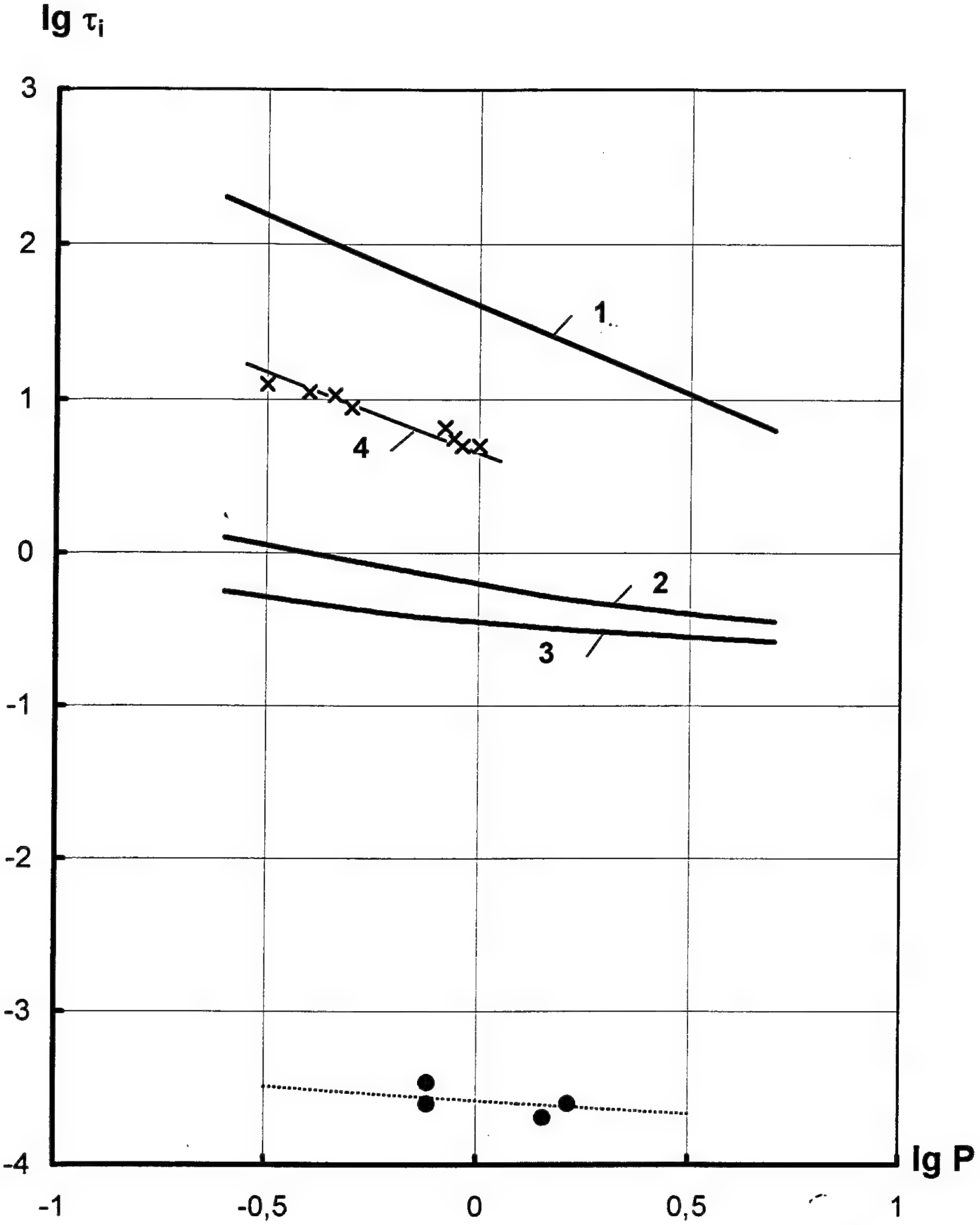


Fig. 4.5.
Dependence of autoignition delay on pressure.
Two-phase kerosene-air mixture, subsonic flow speed,
α = 1.5, d_0 = 100 μm:
1 – T_s = 1000 K; **2** – T_s = 1400 K; **3** – T_s = 1600 K; **4** – T_s = 1173 K
(—— calculated curve and experimental points of Mullins).
● experimental points for supersonic flow.

4.6. Comparison of experimental data with calculated results

For numerical investigation of mixing in the layer of flatly parallel flows of cold fuel and high-temperature supersonic air flow we used a universal system "AeroShape-3D" [25] developed in the Moscow State University, based on the methods of numerical modeling of complex turbulent 3D gas flows. This method provides a satisfactory accuracy on the wide range of Mach numbers and Reynolds numbers at minimal memory and calculation time. Universality and high-efficiency of the method are achieved by application of on finite volume Rectangular Adaptive Mesh (RAM) technique adaptive for the particularities of body shape and of the flow.

In AeroShape-3D the computational grid is created any geometrical bodies. After that, singularities of the shape of these bodies are resolved by rectangular mesh refinement-unrefinement procedure. Here the cells can arbitrary intersect the surface of the body. Adaptation of the mesh to the flow field singularities (shock waves, recalculations, etc.) is also ensured by refinement-unrefinement. Every body can be defined either analytically or by the table. The table method provides rather smooth reproduce curvilinear surfaces on the standard table data.

The applied Rectangular Adaptive Mesh (RAM) technique allows to calculate stationary and non-stationary, sub-, trance-, hypersonic and mixed flows in the 3D areas of a complex shape without any specification of particularities and without specification of areas with one flow type.

Mathematical modeling of combustion processes of hydrocarbon fuel sprayed in the high-temperature supersonic flow takes into consideration inter-phase heat and mass-transfer processes, influence of liquid phase on the turbulent parameters of the flow and chemical reactions.

The results of numerical modeling of kerosene combustion process in the supersonic flow are given on fig. 4.2.

Comparison of calculation results with experimental ones has shown that the "AeroSpace-3D" calculation system can be used for determination of parameters of sprayed kerosene combustion in the supersonic flow.

CONCLUSION

1. The report presents the review of investigations on autoignition of various fuels. The review includes works of both Russian and foreign authors. It systemises the data on autoignition parameters and technical characteristics of the experimental test-benches. The given analysis leads to conclusion that there is a considerable disagreement in ignition delay time measured by different researches, especially at high pressure of the environment. The most likely reason of the disagreement is difference of test-benches and experimental methods.
2. It should be stressed that still there is nozzle any acceptable analysis of interdependence of gas dynamics with chemical reactions.
3. Basing on the studied papers the methods of the experimental investigations have been chosen.
4. The test-bench has been developed, produces and mounted. It allows obtaining the conditions necessary for autoignition of kerosene in heated supersonic air flow.
5. The developed methods and system of measurements allow:
   - to obtain data of the required accuracy;
   - to control the work mode of the object under study and of the experimental conditions.
6. Software package for experimental results processing (in *Object Pascal* for *Delphi*) has been developed.
7. Report gives the results of experimental investigations of kerosene autoignition at the supersonic flow.
8. The obtained experimental data (autoignition temperature T_s and autoignition delay time τ_i) lead to the following conclusions concerning kerosene autoignition at the supersonic flow:
   - Autoignition temperature of kerosene increases along with increase of supersonic flow speed. To obtain autoignition on the distance between

fuel injection point and ignition point and to compensate elevation of flow speed it is necessary to rise kerosene temperature (this temperature is taken as autoignition temperature).

- High relative speeds of air flow and of injected fuel lead to the quick splitting of the fuel jet ($d_o \approx 10...50$ μm) and to intensive evaporation. So it is possible to presume that at the supersonic flow combustion of evaporated fuel has diffusion mechanism. Under these conditions drops diameter does not influence ignition delay time.
- At the supersonic flow ignition delay time is less then ignition delay at the subsonic flow with the same temperature.
- Autoignition delay time in the supersonic flow only slightly depends on the pressure. It can be explained by intensive splitting of fuel drops and it quick evaporation.
- If autoignition is initiated by flameholders or shock waves, even at the same temperature autoignition delay time decreases.

LITERATURE

1. Technical report. Investigation of kerosene autoignition. Contract N F 61708-96-WO286, stage I, 1997, 16 p.
2. Technical report. Investigation of kerosene autoignition. Contract N F 61708-96-WO286, stage II, 1997, 25 p.
3. Fletcher E.A., Dorsch R. and Allen H. Combustion of Highly Reactive Fuels in Supersonic Airstreams. – "ARS J." 1960, INVESTIGATION, v. 30, N 4, pp. 377-344, 11 ill., Bibl. 12 NN.
4. Switenbank J. Experimental Investigation of Hypersonic Ramjets. Collected papers "Process of the International Council of the Aeronautical Sciences. Third Congress – Stockholm 1962", Washington, London, 1964, pp. 951-977, 18 ill., Bibl. 17 NN.
5. Mestre A., Viaud L. Combustion Supersonic dans un Canal Cylindrique. – Collected papers "Supersonic Flow Chemical Processes and Radiative Transfer". Oxford and others 1964, pp. 93-111, 15 ill., Bibl. 7 NN.
6. Stchetinnikov E.S. Phisics of gas combustion. Moscow. Nauka, 1965, 739 p.
7. Mullins B.P., Penner S. Explosions, detonations, flammability and ignition Pergamon Press , 1959, 75 p.
8. Miller R. VII Symposium on Combustion , 1959 , p. 417.
9. Trushin Y.M. Investigation of combustion in flow at high initial temperatures. Third All-Union meeting conference on combustion theory, vol.1, Moscow.: Editing house of USSR Academy of Science, 1960, 79 p.
10. Mestre A., Ducourneau F. Recent studies on the spontaneous ignition of rich air-kerosene mixtures. Combustion Institute European Symposium 1973, pp. 225-229.
11. Wolfer H., VDI-Forchungsheft , N 392, 1939.

12. Laurent F., Bellet J., Soustre J., Manson N. Shock-induced combustion of kerosene with the use of isopropyl nitrate additive. Combustion Institute European Symposium, 1973, pp. 231-235.
13. Samozvantsev M.P. Investigation of combustion in supersonic flow. Moscow.: CIAM, Dissertation, 1967.
14. Zimont V.L., Trushin Y.M. On ignition delay of hydrocarbon fuel at high temperatures. Physics of material combustion, №1, vol. 3, 1967.
15. Kallergis M. Experimentelle Untersuchungen zur Uberschallver-brennung. – Collected papers "Jahrbuch WGLR", 1964, pp. 367-372, 10 ill., Bibl. 6NN.
16. Isaak J. J., Cookson R.A. Supersonic combustion of liquid and gaseous fuels. AIAA Journal, 1973, v.11, N 7 , pp. 1036-1037.
17. Vinigradov V., Kobigsky S., Petrov M. Experimental investigation of liquid carbonhydrogen fuel combustion in cannel at supersonic velocities. AIAA, paper 92-3429, 1992.
18. Suttrop F. Experiments on methods for improved fuel ignition in scramjet combustion systems. ICAS, paper , N 15, 1972.
19. Billig F., Waltrup P., Stockbrige R. Integral-rocket dual-combustion ramjet. Fourth ISABE proceedings, 1979.
20. Prudnikov A.G., Volinsky M.S., Sagalovich V.N. Process of mixing and combustion in ramjets. Moscow.: Mashinostroenie, 1971, 355 p.
21. Abramovich G.N., Krasheninnikov S.Y., Secundov A.N. Turbulent flows at interaction of volume forces and non-auto-modeling, Moscow.: Mashinostroenie, 1975, 94 p.
22. Kudriavtsev A.V. Influence of fuel evaporation on the ignition delay time of two-phase mixtures. In "Combustion physics". Kiev: Naukova dumka, 1966. pp. 94-103.
23. Ditiatkin Y.F., Kliachko L.A., Novikov B.V., Yagodkin V.I. and the others. Liquid spraying. Moscow: Mashinostroenie, 1977, 208 p.

24. Rutovsky V.B. Investigation of self-ignition in the combustion chambers of bypass ramjet. IUTAM Symposium on «Combustion in Supersonic Flows», Poitier, France, 1995.
25. Mullins B.P. Studies on the spontaneous ignition of fuels injected into hot air stream. Fuel, 1953, vol. 32, N 2, 3, 4.
26. Hagemann G., Schley C.A., Odintsov E., Sobatchkin A. 3D-Plug-Claster Flowfield Analysis, AIAA 96-2954, Lake Buena Vista, Florida, 1996.